DEVELOPMENT OF A WEB-BASED OFF-HIGHWAY PLANT INFORMATION SYSTEM

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Signature ....

Date 6/3/03

Abstract

The advantages of plant utilisation in off-highway activities such as construction, mining, forestry, etc can never be over-emphasised. As a result of the enormous demand placed on this valuable resource, documentation has become paramount in their effective utilisation. Such documentation relate to inventories, maintenance records, costs, utilisation and breakdown records, etc.

Several efforts have been made in order to institute an efficient plant history information regime. These ranged from traditional paper- based to the ("relatively newer") IT-based methods. However, a literature review and pilot study reveal that these are yet to cope with the dynamism with which historical data are generated. Also, when compared with other similar "advanced industries" such as aviation shipping, railways and roads; off-highway plant lags behind in the application of web-based 'intelligent' information systems.

This research sought to improve off-highway plant information management through the development and application of INTELLIPLANT, a web-based information system. The system evolved as an integration of a web-based Relational Database Management System (RDBMS) and a Model Base Management System (MBMS). The RDBMS was designed from the forms collected during a pilot/ field investigation, while the MBMS emerged from the assemblage of time series models developed from a rigorous analytical procedure. INTELLIPLANT has the capacity to generate over 20 real-time history reports on-line through its RDBMS structure. In addition, the MBMS models predict plant breakdown time (BDPERC) as a percentage of plant availability time for wheel loaders, backhoe-loaders, hydraulic excavators and off-highway haulers. The models depend on the lagged BDPERC, percentage utilisation (UTILPERC), standby percentage (SBPERC) and fault occurrence percentage (FLTPERC). Model validation results indicated acceptable MAD and RMSE performance statistics for each model. Also, results from the practitioner-led performance evaluation of the system indicated that the development of INTELLIPLANT is a significant contribution to off-highway plant history information management.

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Dedication

To: LOLA, TOBI, TOSIN and TOFUNMI

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER ONE: Introduction

INTRODUCTION

Information Technology (IT) is defined as the use of electronic machines and programmes for the processing, storage, transfer and presentation of information (Rivard, 2000). It encompasses many technologies including computers, software, Intranets and the Internet and even telephones and fax machines. IT aims to facilitate the exchange and management of information by creating new possibilities for more effective communication, and data accessibility between project participants (Newton and Sharpe, 1994; Rivard, 2000). IT enables great improvements in the collection, storage, analysis and transmission of information to be made by enhancing the speed with which each activity is conducted. IT is no longer just viewed as being merely an enhancement to traditional business procedure, but rather, an innovative conduit that enables new and different ways of organising and operating business enterprises to emerge (Ahmed *et al*, 1995). The positive impact of IT throughout industry has thus been described as a key enabler of modern information management (Maxwell, 1995; Love, *et al*, 1997).

Global networking and rapid technological product innovation are key developments in the information age and are changing the way businesses operate (Auoad and Sun, 1999). To meet this trend, various IT solutions have been developed. These range from simple computer programmes to intelligent systems, which aid decision makers in complex decision situations (Chen *et al*, 1994; Klein and Methlie, 1995; Famili *et al*, 1996; Bertino *et al*, 2000). The advent of the Internet is a significant phenomenon to IT solutions in recent years. The Internet is a permanently linked global collection of computer networks (servers) providing a vast and easily source of information and data (Sugumara and Storey, 2000; Dillinger, 2000). The Internet acts as a catalyst through which enhancements of communication processes can be made (Vakola and Rezgui, 2000; Rivard, 2000). In turn, various IT frontiers have been expanded in order to improve knowledge boundaries and deliver better solutions to industry (Faraj *et al*, 1999; Rivard, 2000).

Many industries in the developed world are confronted with a crisis of restructure; that is, efforts geared towards enhancing business performance (Love *et al*, 1997). This crisis is founded on management's continual rethinking and refocusing of current production processes and workflows, with the aim of adding value to production processes and products (Michael, 1997). Many businesses perceive IT applications as a viable means of resolving this crisis (Vakola and Rezgui, 2000; Rivard, 2000). Several surveys were conducted recently to determine the likely/probable impact of IT throughout industry in various developed countries (Maxwell, 1991; Rivard, 2000). These countries include the UK, New Zealand, Sweden, Denmark, Finland, Hong Kong, Saudi Arabia and Canada. Results provide anecdotal evidence that IT applications have positively replaced many traditional business processes and enhanced organisational productivity and performance.

A Background to Innovative Practices

In addition to IT, numerous technological and management techniques have been introduced throughout industry under the banner of higher efficiency (in the form of cost and time), quality and better customer value (in terms of performance and zerodefects) (Bjork and Turk, 2000). These include concepts such as public-private partnerships, partnering, value management, benchmarking and standardisation and prefabrication (Michael, 1997; Anon, 1998). Although, these are all performance improvement tools and techniques, standardisation and prefabrication deal with the physical works, while the others relate to project planning and management (Sawers, 1999).

Despite all the aforementioned efforts to improve management and technologies, modern projects have become much more ambitious (Carroll, 2000). Consequently, they become associated with tight project delivery times (Wright, 1997; Carroll, 2000; Hendrickson, 2000). Also, the reduction in delivery time often creates an increase in labour costs (Nunnally, 2000). Therefore, as labour costs increase, so do the benefits of using machinery (Canter, 1993; Edwards *et al.*, 2002).

OFF-HIGHWAY PLANT UTILISATION

The development of off-highway plant and equipment has become increasingly sophisticated over the years (Canter, 1993; Edwards *et al*, 2002). "Off-highway plant", in this instance, takes into cognisance equipment used in construction, demolition, aggregate production, mineral extraction and similar activities. Examples of recent developments include the introduction of Geographical Positioning (GPS) systems for plant tracking and navigation, data tagging to facilitate maintenance of plant items and on-board condition monitoring (Edwards, *et al*, 1998; Anon. 2002a). It is also envisaged that more machines will be invented or adapted as a result of the benefits of machine usage (Lundegard, 1998). Benefits include, reduction in costly labour input, faster project delivery and efficiency of quality control (Canter, 1993; Carroll, 2000).

Successful project management in the off-highway sector thus seeks to satisfy the requirements of project plans and specifications within contractual periods and economical costs (Canter, 1993, Hendrickson 2000). There are over 200,000 mobile plant items in the UK alone at any given time and this capital investment cost equates to approximately £12 billion. This massive investment has to be managed correctly (Edwards *et al*, 2001). Equipment selection and management is a vital factor as it represents one of the largest long-term 'company' capital investments (Day and Benjamin, 1991). Such investments also tie up liquidity in respect of purchases and hire costs. Careful consideration must therefore be given to: its selection; the methods of acquisition; the monitoring of usage and performance; and fleet maintenance (Canter, 1993; Nunnally, 2000; Edwards *et al*, 2002). To achieve optimal efficiency of plant utilisation and plant economics, effective plant information management is imperative (Edwards *et al* 1998; Nunnally, 2000).

PLANT INFORMATION MANAGEMENT

Plant information management involves the process of collating important organisational documentation for subsequent retrieval, assessment and/or analysis and subsequent dissemination (Rowley and Butcher, 1998). With respect to plant management, three major classifications of information management methods are available, these include:

i. the traditional (paper-based) techniques;

ii. the IT based techniques; and

iii. the Internet based information management systems.

Traditional Plant Information Management Techniques

Traditional plant information management techniques refer to paper-based formats for managing plant data (Boyd, 1995). Examples of existing paper-based formats include: plant inventory, maintenance programme, machine maintenance report, machine cost estimation, maintenance planning charts, and history file data (Edwards, *et al*, 1998). These forms enable various plant history data (where plant history data refers to data recorded in respect of inventories, maintenance, etc) to be captured. Table 1.1 gives a brief description of each form and its use. The traditional method entails the utilisation of the forms to coordinate plant management from inventories to maintenance planning and reporting (McCaffer and Thorpe, 1992). All information relating to updates on plant items such as new purchases, costs, inter-site transfers and depletions are manually recorded (on paper) based on new information being received (Boyd, 1995). The traditional method also entails the manual recording of (on paper) maintenance activities and planned maintenance programmes using Gantt charts and similar planning techniques (Felton, 2000; Lewis and Steinberg, 2001). Information retrieval based on this method is also manual and entails the searching and manipulation of the historical data for the appropriate information of interest (Bjork, 1999; Nunally, 2000).

Table 1.1: Description of Paper-based Formats of Plant Documentation

S/ No.	Form	Description
1.	Plant Inventory	Provides a readily available source of information on plant status, e.g. additions, depletions, replacements and location.
2.	Maintenance Programme	Provides specifications for the individual plant items relating to the methodology and frequency of maintenance required.
3.	Machine Maintenance Report	A factual recording by 'hands-on' engineers of maintenance conducted on plant items but they also include a subjective statement of general maintenance condition.
4.	Machine Cost Estimation	Used to plan for future cost expenditure and control current cost expenditure.
5.	Maintenance Planning Charts	Provide details on: what maintenance activities have to be done; statutory safety inspection; the order in which activities should be carried out; identification of staff assigned to particular activities and when activities are to be completed.
6.	History File Data	Supplies a readily available quick reference guide from which senior management can analyse the inherent success or failure of their maintenance policy.

IT Based Plant Information Management Techniques

IT based management techniques describe systems that require computers for historical data capture and manipulation (Canter, 1993). The growth of IT applications in plant management originated from rapid technological developments and subsequent knowledge transfer across industrial boundaries as companies aspired to streamline business efficiency in order to realise greater profitability (Nunnally, 2000). However, one of the greatest impacts of IT applications in plant management is the reduction in paper or 'hard copy' volumes required for collecting and storing plant data (Maxwell, 1991; Rowley and Butcher, 1998). This is quite notable because keeping track of, organising, controlling and supervising equipment management can consume a significant amount of time and company resources that impact on project progress (Edwards, *et al* 1996; Anon 2000b; Lewis and Steinberg, 2001).

Commercial Software Packages

Existing commercial software typically comprises of a file system and/or a relational database management system resident on PC's or local networks (Boyd, 1995; Lundegard, 1998). Caterpillar, one of the world's leading plant manufacturers and suppliers have produced a number of commercially available software for plant history data management. Their main applications are detailed in table 1.2 (Anon, 2002a).

Table 1.2: Other Available Caterpillar Software

SOFTWARE	APPLICATION
Cat Marine Power Pro	Electronic documentation about Caterpillar Engines
Cat Truck Engine Pro	Critical Data about Caterpillar truck engines
Customer Communications Module	Communicate with electronics on generator sets
Caterpillar Dataview	View machine data from sensors
DozSim	Dozer simulation software
Equipment Investment Analysis	Caterpillar performance handbook
Electric Power Generation Designer	Size, spec and installation
Caterpillar Electronic Technician	Accesses the machines' electronic system
Fleet Production and Cost analysis	Estimates production rates and cost of equipment
Payload Calculation System	Download payload control system
Repair, Rebuild or Replace Analysis (RRR)	Analysis of equipment alternatives
Truck Payload Measurement System	Configures TPMS control module and information
Vital Information Management System	Configures and Support onboard VIMS
Wheel Loader Payload Measurement System	Configures on board WPMS controls system

(Source: CAT circa 2002)

Similarly, software developed by other manufacturers includes the following:

i) Customised Plant Management (CPM), by Greg Sier & Associates, which aims to provide a comprehensive mono-software solution to plant management. The capabilities of the programme include: detailed employee systems with training and skills databases; safety systems for segmenting areas and responsibilities in the work place; scheduling inspections; tracking non-compliances; and separate cataloguing and inventory systems (Anon, 2000b). Quick Maintenance (QM) is a subset of CPM emphasising plant maintenance record management, plant history, asset recording and inventory.

ii) ROADWORK and MAINWORK, by Homegrown Software, (Anon 2000c). This programme facilitates the: tracking of revenues generated by equipment; computation of expenses incurred; creation of dispatch schedules for equipment; and tracking of repair cost of parts and labour by equipment number.

A common characteristic of the above systems is that they provide a means whereby equipment can be managed efficiently. This they achieve by operating within a standalone environment. The historical records hosted by the systems are used to facilitate the tracking of equipment operational parameters such as inventories, maintenance and despatch schedules.

Internet Based Information Management Systems

The introduction of the Internet along with the advances in three-tier architectures and middleware technologies has brought new challenges and competitive advantages to IT development (Vakola and Rezgui, 2000). Three-tier architectures refer to the development of Internet based systems that comprise of: (i) a first-tier (front-end) user interface; (ii) a second-tier web server system; and (iii) a third-tier (back-end) database system (Liang and Garret, 2000). Middleware technologies are newly developed software solutions, which facilitate the design of the web server (second-tier) systems as a means of enhancing the efficiency of traditional client/server (two-tier) architectures (Baek, *et al* 1998; Greenspum, 1999). Very recently, Ironmax Inc. developed and launched a new suite of three-tier information tools for on-line access for sellers, buyers and managers of construction equipment (Anon, 2001a). The tools allow on-line access to various plant management references containing information on: the latest plant auction sales results; equipment values; and a guide to ownership and operating costs. Benefits of the Ironmax system include the provision of on-line access to latest equipment values and information on costs of operating plant items, which could serve as a guide to intending users.

PLANT INFORMATION MANAGEMENT RESEARCH: CURRENT STATUS

Existing traditional and IT methods of managing plant information data represent the product of various research efforts to date (Barton, 1985; Boyd, 1995; Edwards *et al*, 1998). Certain limitations have however been attributed to these methods (Oloke *et al*, 2001). These are:

i) Paper-based methods generate bulky documentation that requires extensive storage space and time consuming management.

ii) Special hardware and (especially) software management skills must be acquired in order to utilise most electronic methods currently available (Anon, 2000c).

iii) The mathematical models for plant performance assessment, (running costs and operational 'production' (which the current electronic systems are based on) contain adjustment factors that are determined purely from subjective experience and intuition (Hendrickson, 2000).

iv) Users are confronted with the inability to interpret reports generated by such systems unless of course, lengthy manual mathematical manipulation of the data is employed (Edwards *et al*, 1998).

Based upon the culmination of these findings, it is proposed that the determination of the model prediction variables should be re-evaluated. The variables should be determined based on continuous observation of machines working under a myriad of operational conditions (Nunnally, 2000; Hendrickson, 2000). However, earlier research recommended that any new IT development should be based on extensive industrial collaboration in order to guarantee its long-term implementation (Lundegard, 1998; Edwards, 1999).

AIMS AND OBJECTIVES OF THIS RESEARCH

The review of existing plant information management systems, exposed two major areas where research is required. These are: (i) improvement on the decision support capabilities of plant information management systems and (ii) enhancement of automated data collection, retrieval and transmission techniques. In order to address these, a web-based 'intelligent' information management system (INTELLIPLANT) is hereby proposed and subsequently developed. The system aspires to provide a useful management tool with which to capture, monitor, control and predict aspects of the plant data gathered. Initially, INTELLIPLANT focuses on the modelling of plant breakdown duration forecasts; albeit, this should not preclude extension to other types of performance data at a latter date. The web-based system allows ease of information accessibility and database update from remote locations (Scott *et al*, 1998; Sun *et al*, 1999; Felton, 2000; Liang and Garret, 2000). On the other hand, the system's 'intelligence' eliminates the rigours associated with manual manipulation of automated reports generated by the system (Zhang, 1999; Turban and Aronson, 2001).

The main aim of this research is to substantially improve off-highway plant information management through the development of INTELLIPLANT. In achieving this aim, the following principal objectives will be simultaneously realised:

i) to review relevant literature associated with off-highway plant information management science. This enabled a compilation and study of existing methodologies and the subsequent development of a strategy for improving these systems;

ii) to collect plant history file data and data capture mechanisms from various sources such as plant manufacturers, plant users and other practitioners. This was achieved through the administration of questionnaires, telephone interviews, site visits and e-mail enquiries;

iii) to model, analyse and validate plant breakdown data collected using deterministic analysis techniques; and

iv) to develop an 'intelligent' web-based plant information management system for plant users. The system will incorporate validated report sheets on plant history and plant breakdown prediction models developed during the research.

'INTELLIGENT SYSTEM' AS USED IN THIS THESIS

Drawing from established principles of intelligent systems (Sun *et al*, 1999; Zhang 1999; Guohua, 2000; Turban and Aronson, 2001); this research focuses on the development of INTELLIPLANT as a tool for enhanced off-highway plant information system. INTELLIPLANT was therefore conceived as an 'intelligent system' that utilises mathematical models – whose purposes may be for structure analysis and future prediction of plant history parameters (Guohua, 2000). Turban and Aronson (2001) recommended the development and integration of: data management subsystem (database); model management subsystem; knowledge management subsystem and the user interface subsystem in the development of an intelligent information system. Albeit, the knowledge base management subsystem is described as an option which can support any of the subsystems or act as an independent component to provide augmented intelligence to that of the decision maker (Bertinio *et al* 2001).

'Intelligent system' as used in this research, therefore, implies an information system developed based on an integration of a database structure, model base system and a user interface. The model base system was developed to ensure the system's capability of providing additional (futuristic) information based on historical records stored in the database (Famili *et al*, 1996).

BENEFITS AND BENEFICIARIES OF THE RESEARCH

INTELLIPLANT is expected to be a useful tool for various end-users within the off-highway plant sector. These include plant managers, plant maintenance engineers and operations/site managers amongst others. This is because the INTELLIPLANT system eliminates the traditional burdens associated with paper documentation; enhances system accessibility from numerous remote locations; and provides better plant information management decision support. This system represents a more efficient and effective means of managing plant history records. In addition and due to its improved decision support capabilities, the system would assure higher profit margins for its users.

The newly developed system would facilitate the benchmarking of different plant items' performance. This will assist plant managers in selecting the plant with the most suitable productivity parameters requirement for a proposed activity (Nasser, 2001). This decision support capability will also aid the development of an efficient plant management programme. This will be as a result of management being able to predict plant breakdown events and durations as well as generating real time on-line reports of the fleet from various geographical locations.

The system's predictive capability is a major advancement over existing systems. The system utilises time series models to predict breakdown time for specific machines based upon their operating history. This significant research contribution will allow plant manufacturers (who monitor warranty costs on their machines) to identify recurring faults and thereby enable the determination of associated costs.

FRAMEWORK OF RESEARCH

To provide direction and define scope, a conceptual framework for the intended research work was developed. This ensured that an holistic study of the research problem was made. The framework also facilitated the development of an efficient

INTELLIPLANT system methodology. The framework was classified into seven distinct stages (Figure 1.1). Each of these stages is described in turn under the following sections of the thesis.

Stage 1: Introduction

As an initial step, the research problem was defined and the need to establish an intelligent off-highway plant information management system evaluated. A literature review of the existing systems and current research was made in order to articulate the research objectives in the context of current and future developments. The review also identified inherent setbacks residing within existing systems, thereby ensuring that the new system overcomes these.

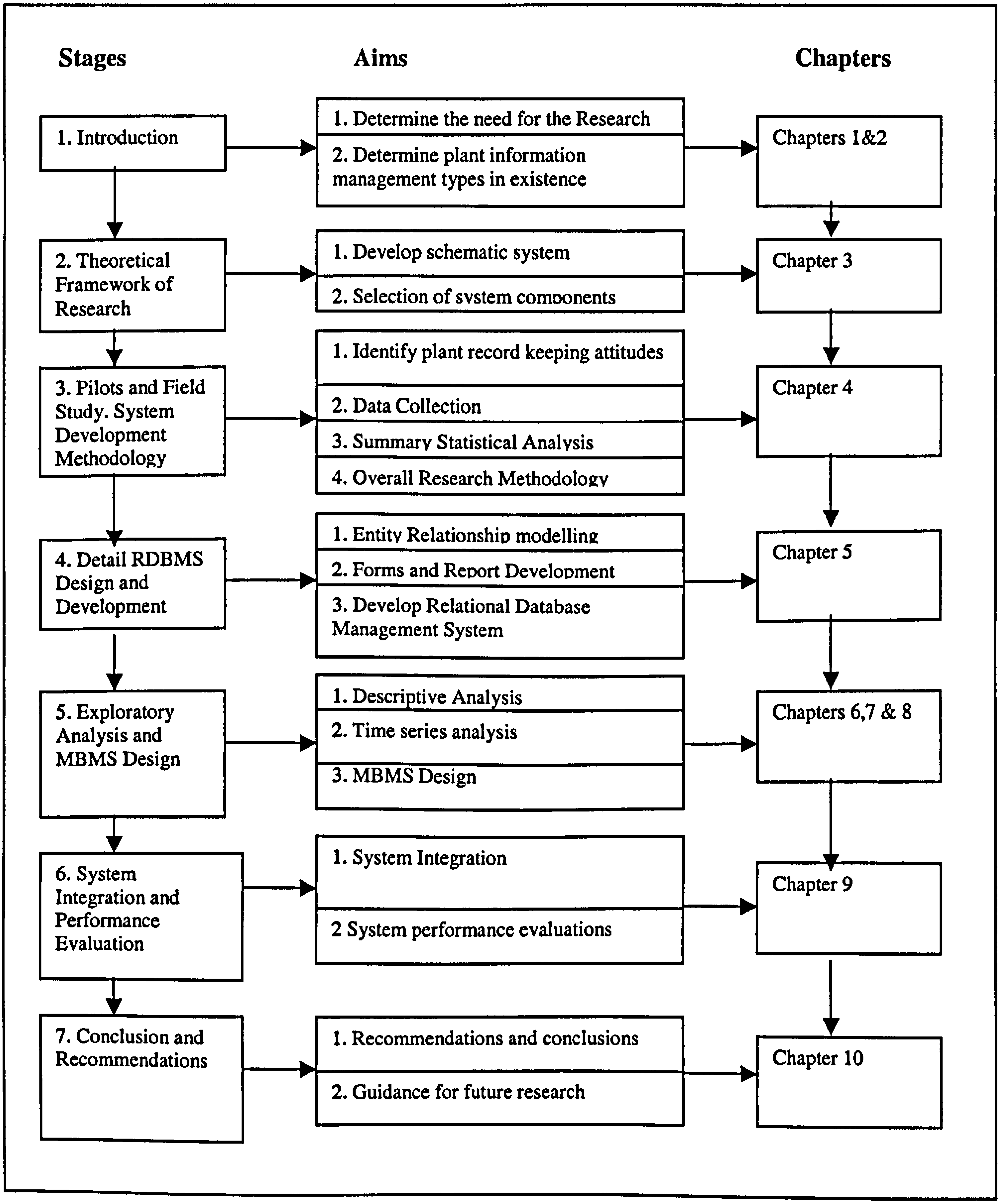
Stage 2: Theoretical Framework of Research

During this stage the theoretical concepts for the development of intelligent systems were reviewed. This review enabled the design of a 'conceptual' schematic system that should efficiently satisfy the research objectives. The conceptualisation of the intelligent web based plant information management system (INTELLIPLANT) essentially determined the system components and how each component was integrated together.

Stage 3: Pilot Study and System Development Methodology

The pilot study sought to identify the record keeping techniques currently being utilised in the UK. Based upon this initial study, a more extensive field investigation was conducted and sought to elicit the value placed on plant information management by practitioners. The reasons proffered for not utilising formal plant information management techniques by certain practitioners (such as systems requirements, accessibility, financial considerations, etc) were incorporated into the new system's design.

Figure 1.1: Research Methodology and Thesis Layout



A system development methodology was therefore evolved for INTELLIPLANT. Two major components were defined as: the Relational Database Management System (RDBMS) and the Model Base Management System (MBMS). The RDBMS captures and manages plant history data in such a manner that reports and forms could easily be automatically generated on-line, while the MBMS hosts the models for predicting plant breakdown percentage time.

Stage 4: Detail RDBMS Design and Development

A detailed description of the RDBMS and procedure adopted for its design is given. The RDBMS was designed through an iterative process of entity type selection, formation of attributes, normalisation and modification of attributes and entity types until the optimal design was achieved. The RDBMS contains input forms for plant inventories, specification, maintenance, health and safety records and costs. The system was designed using MS Access 2000 and programmed in Visual Basic Applications (VBA) for MS Access 2000.

Stage 5: Exploratory Analysis and Model Base Management System Design

This stage commenced with a descriptive analysis of plant history data. The objective was to identify key plant information management variables that enabled further exploratory analysis. Particularly, the incidence of fault occurrence, plant utilisation, standby and breakdown frequencies in addition to plant working environments were examined as part of the descriptive analysis procedure of the historical data.

Furthermore, a rigorous exploratory analysis led to the conception of a time series model for predicting plant breakdown time as a percentage of plant working time. The model was developed by selecting the best technique between the exponential smoothing and Autoregressive Integrated Moving Average (ARIMA). The ARIMA procedure was selected because it identified prevalent patterns in the observed series and uses these to predict new values. Four parameters are estimated. They include: alpha – the general parameter; gamma – the trend parameter; delta – the seasonality parameter; and phi – the dampening parameter. The plant breakdown time series were divided into two periods; historical (estimation) and validation (hold-out) periods. The data in the validation period were used to validate the models developed from the historical period.

The ARIMA model building procedure was used to develop plant breakdown prediction for four plant items namely: wheel loaders, backhoe-loaders, hydraulic excavators and off-highway loaders. These time series models were then organised into the model library of the MBMS of INTELLIPLANT.

Stage 6: System Integration and Performance Evaluation

During this stage of the research, the RDBMS and the MBMS were integrated as a unit to form INTELLIPLANT. The integrated unit was then web-enabled using data access pages. Each section of the forms and reports contained on INTELLIPLANT was made a data access page to facilitate the access to those components of the system via the Internet.

A performance evaluation was then carried out utilising historical data supplied by collaborating practitioners. The procedure entailed the posting of the data onto INTELLIPLANT and system performance monitoring online. Performance checks included: the ease of navigating the system pages, the rate of generating (and the real time accuracy) of reports and assessment of predicted plant breakdown time.

Stage 7: Conclusions and Recommendations

The major findings from this research and recommendation of areas for future research were presented. Further work, past this initial research, will apply methodologies presented to other areas of plant performance (e.g. plant utilisation, cycle times and so forth). Further research is also expected to investigate the development of a case-based reasoning knowledge base management system to interface with the RDBMS.

GUIDE TO THE THESIS

Chapter 2: Provides a detailed literature review. The review consisted of the evaluation of existing plant information management systems. It similarly assessed the status of plant information management research. Sources of information include journal publications, past PhD thesis, conference publications, the World Wide Web and practitioner publications. The literature review also enabled a comparative analysis of the plant IT advancements made in 'more advanced' industries such as aviation, shipping and railway management. The analysis revealed that these industries are maximising the benefits of web enabled IT systems in the management of plant operations and information management. These findings provided distinctive guidance for developing the concepts for the proposed intelligent web-based off-highway plant information management system.

Chapter 3: The theoretical concept for the development of the intelligent web based off-highway plant information management system was extensively discussed. The need for the system was emphasised and the factors influencing the selection of the system components were individually evaluated. The selected system components include the RDBMS and the MBMS. The chapter also gives an overview of the theory of the relevant system architecture.

Chapter 4: Details of the pilot and field studies are discussed. The pilot study 's principal objective was to identify existing plant record keeping techniques and general 'attitudes' towards plant information management by plant users. The chapter describes the methods applied in collecting data entry forms and plant history data and presents a summary of practitioner responses received. Findings from the pilot study formed the basis on which the RDBMS and the MBMS were subsequently designed. The chapter also gives an overview of the system development methodology.

Chapter 5: Specific details of the RDBMS are given in terms of concept, design and the development. These processes were systematically presented. The steps for the development include the design of the entity-relationship model and the design of the data input and plant information management reports. In addition, a comparative analysis of the advantages and disadvantages of the available RDBMS systems was presented. The data input capabilities of the RDBMS were formulated by the development of user-friendly forms. Each of the forms could capture data relating to pertinent plant history parameters such as inventories, maintenance, etc. the RDBMS was also designed with the capabilities of generating real time on-line reports based on the historical records contained within the database.

Chapter 6: Descriptive statistics of off-highway plant information data for plant breakdown prediction are presented. The influence of plant breakdown events on effective plant utilisation was critically investigated with a view to evolving modelling techniques for plant breakdown. Various modelling techniques (for example artificial neural networks, genetic algorithms, rule induction and time series techniques) were reviewed. The time series technique was selected because of its suitability for modelling plant breakdown.

Chapter 7: A time series analysis procedure used for modelling off-highway plant maintenance breakdown was described. The process involved model identification (plotting the series and plotting correlation functions), parameter estimation (using exponential smoothening and the ARIMA procedure) and diagnosis. The seasonal decomposition procedure is used to estimate multiplicative or additive seasonal factors for periodic time series. Thus, new series containing seasonally adjusted values, seasonal factors trend and cycle components, and error components are automatically added to the working data file for further analysis. Using the Box-Jenkins approach, however, the model fit is assessed using automatic residual and confidence-interval series generated along with the forecasts. Standard errors and other statistics also help to judge the significance of the coefficients estimated for the models. The model building procedure entailed the rigorous simulation of four cases in which the independent variables (the lagged plant percentage breakdown, fault occurrence percentage, utilisation percentage and standby percentage) were severally combined in order to select the best combination. The selected model was based on case IV (in which all the independent variables were used) for the wheel loader model.

Chapter 8: Using the selected case IV, historical data from other plant models such as the backhoe-loader, hydraulic excavator and the off-highway hauler were also simulated. This facilitated the development of additional plant percentage time breakdown prediction models. The models were also individually validated in order to ensure their robustness and predictive capabilities. On the average, the models produced a performance statistics with MAD = 5.03 percent and RMSE = 5.33 per cent. A library of plant breakdown percentage models was subsequently developed from the four models as part of the MBMS of INTELLIPLANT. The GUI of the MBMS was also designed, thus ensuring that the MBMS was finalised.

Chapters 9: A system integration and performance evaluation was conducted in this chapter. The procedure used to integrate the system and set up the performance evaluation standards was presented. In addition, the chapter presents a summary of the feedback received from the collaborating organisations.

Chapter 10: This chapter examined a fulfilment of the objectives of the research. It also presented the conclusions and recommendations that arose from the work. Finally, areas in which additional work could be carried out in future were critically examined.

ACADEMIC ACHIEVEMENTS

The main academic achievements arising from the research are summarised as follows:

- (i) the identification of problems associated with the utilisation of current off-highway plant information management systems;
- (ii) the development of a robust, web enabled plant history relational database management system;
- (iii) the development of a model base system useful for the prediction of plant breakdown percentage time based on historical breakdown, standby, utilisation and fault occurrence records; and
- (iv) the development of INTELLIPLANT. A system that integrates the RDBMS and MBMS to enhance plant information management decision support.

As part of the strategies to disseminate the various findings emanating from this research to industry and to engender wider academic debate, the research produced some research papers. The titles and bibliographic details are presented as follows:

1. Intelligent Construction Plant Information Management (2001).

   Oloke, D.A., D.J. Edwards, and B. Li (2001), Intelligent Construction Plant Information Management, Proceedings of the 17th Annual ARCOM Conference, Salford, UK. Edited by Akintola Akintoye

2. A Data Capture Mechanism for Modelling Construction Plant Breakdown and Maintenance Costs (2001)

Oloke, D. A and Edwards, D. J (2001) A Data Capture Mechanism for Modelling Construction Plant Breakdown and Maintenance Costs. Proceedings of the ARCOM doctoral research workshop: Simulation and modelling in construction. University of Edinburgh, October. http://www.arcom.ac.uk/workshops/04-Edinburgh.html

3. A Knowledge Based Representation Approach to Construction Plant Maintenance Cost Assessment (2002)

   Oloke, D.A and Edwards, D.J (2001) A Knowledge Based Representation Approach to Construction Plant Maintenance Cost Assessment (2001). Proceedings of the Second International Post Graduate Research Conference. University of Salford, UK. April 11th and 12th, Edited by Sun, M., *et al.*

4. An Intelligent System for Improving Plant Information Management (2002)

   Oloke, D.A and Edwards, D.J. (2002) An Intelligent System for Improving Plant Information Management (Accepted for publication in International Journal of IT in Architecture, Engineering and Construction (IT-AEC), 2002).

5. Predicting Plant Breakdown using the Time Series Approach (Being Refereed, 2002)

   Oloke. D.A, Edwards, D.J and Nicholas, J. (2002) Predicting Plant Breakdown using the Time Series Analysis (Being Refereed, 2002) for publication in the Journal for Structural Survey.

CHAPTER TWO: Information Management Systems- A Review of the Off-Highway Plant and Associated Industries

INTRODUCTION

In a well-structured organisation where top, middle and lower level management are clearly defined, documentation provides a formal 'written' description of the company's operational requirements (Maxwell, 1991). Documentation assists in the execution of various 'operational' work processes and aids staff to perform tasks to prescribed standards (Chan *et al.*, 1998). Management of information contained in such documentation includes: organisation-wide information policy planning; the development and maintenance of integrated systems and services (De Brito and Branco, 1998). It also includes the optimisation of information flows and the harnessing of leading edge technologies to the functional requirements of end-users, whatever their status or role in the parent organisation (Rowley and Butcher, 1998). In plant management, information flow facilitates policy planning relating to purchase, operation and maintenance of plant items (Wetzel, 1998; Nunnally, 2000).

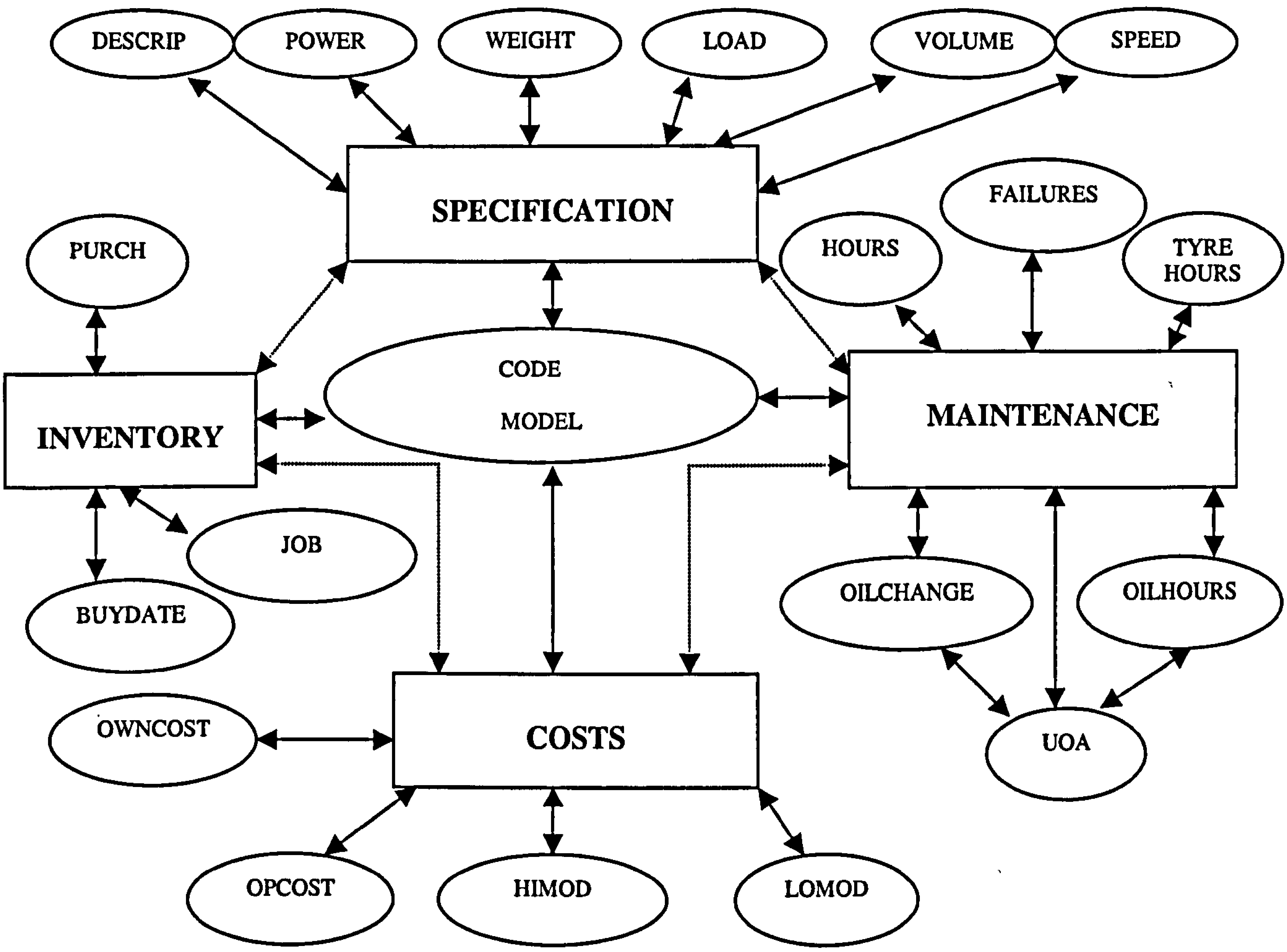
This literature review chapter is an in-depth assessment of existing plant information management techniques. It commences with the classification of these management systems based on the platforms they operate (i.e. PC, local network or Internet/Intranets). The advantages and limitations of each were also assessed in order to explore opportunities for improvement. The review further examined information management techniques in some other 'more technologically advanced' industries. These include aviation, shipping, railways and roads. These industries had similar information management needs (such as inventories, maintenance, etc.) when compared with the off-highway plant sector. A review of each of these industries was made in order to understand and formulate appropriate strategies for technology transfer to the off-highway plant sector.

Finally, a review of recent information management system developments used in other engineering applications was also conducted. Findings from the reviews enabled an assessment of the current status of off-highway plant information management in relation to other industrial sectors to be made.

A CLASSIFICATION OF EXISTING PLANT INFORMATION MANAGEMENT SYSTEMS

Plant information management revolves around a typical dataflow structure as exhibited diagrammatically in Figure 2.1. Typical data files are machine specifications and inventories, maintenance and service costs (McCaffer and Thorpe, 1992; Boyd, 1995). Machine code and model numbers are common file attributes as these enable management to track expenditure and maintenance activities for individual items (Barton, 1985; Boyd, 1995). Other parameters such as: engine power, oil change frequency, purchase date and so on are more specific files and less widely used.

Figure 2.1: Typical Plant Information Dataflow Structure (Source: Oloke et al, 2001)



<u>Legend:</u>

MODEL	Manufacturer's model number
DESCRIP	Description of machine
POWER	Combined engine power in KW
WEIGHT	Empty weight in KG
LOAD	Load capacity in KG
VOLUME	Volume capacity in cum.
SPEED	Maximum speed in KM/hour
CODE	Alphanumeric machine ID code
BUYDATE	Date of machine purchase (y/m/d)
PURCH	Initial purchase cost
JOB	Job codes where machine is located
OWNCOST	Hourly ownership (average)
OPCOST	Hourly operating cost
HIMOD	Cost multiplier for severe conditions
LOMOD	Cost multiplier for easy conditions
HOURS	Current engine hours
OILFREQ	Freq. of need for oil change (hrs)
OILHRS	Engine hours at the last oil change
UOA	Used oil analysis result
TYREHRS	Engine hrs. after installing new tyres
FAILURES	Cum. number of in-service b/downs

For brevity, it can be summarised that three broad categories of IT based plant information management systems currently exist (Oloke *et al.,* 2001). These categories are based on their operational platform and include:

i) category 1: file system and/ or relational databases for checking plant specifications. These are usually stand alones resident on PC's;

ii) category 2: file systems and/or relational databases for monitoring plant inventories and maintenance records. The are usually resident on local networks; and

iii) category 3: file systems and/or relational databases for plant hire and sales. These are recently developed and are usually resident on the Internet.

A major limitation with the three categories defined is the need to purchase costly hardware and software, which invariably becomes obsolete. (Oloke and Edwards, 2002a). However, with systems under category 1, users must also invest heavily into employee training and periodic system upgrades in order to enhance software performance. A typical illustration, which depicts information flow within PC-based systems, is provided in Figure 2.2. This Figure reveals that information is transmitted from each plant site to a central database through the database manager who processes centrally and subsequently publishes results. Hence, the system restricts flow of information between plant sites and the co-ordinating head office. Free flowing information is however important because information *per se* is an invaluable resource. Not least because the performance of plant and the company can be determined by the intelligent manipulation of such. Information also allows the plant management strategy to be commissioned and subsequently implemented efficiently and effectively throughout the organisation (McCaffer and Thorpe, 1992).

Figure 2.2: File Systems and Relational Databases Resident on PC's

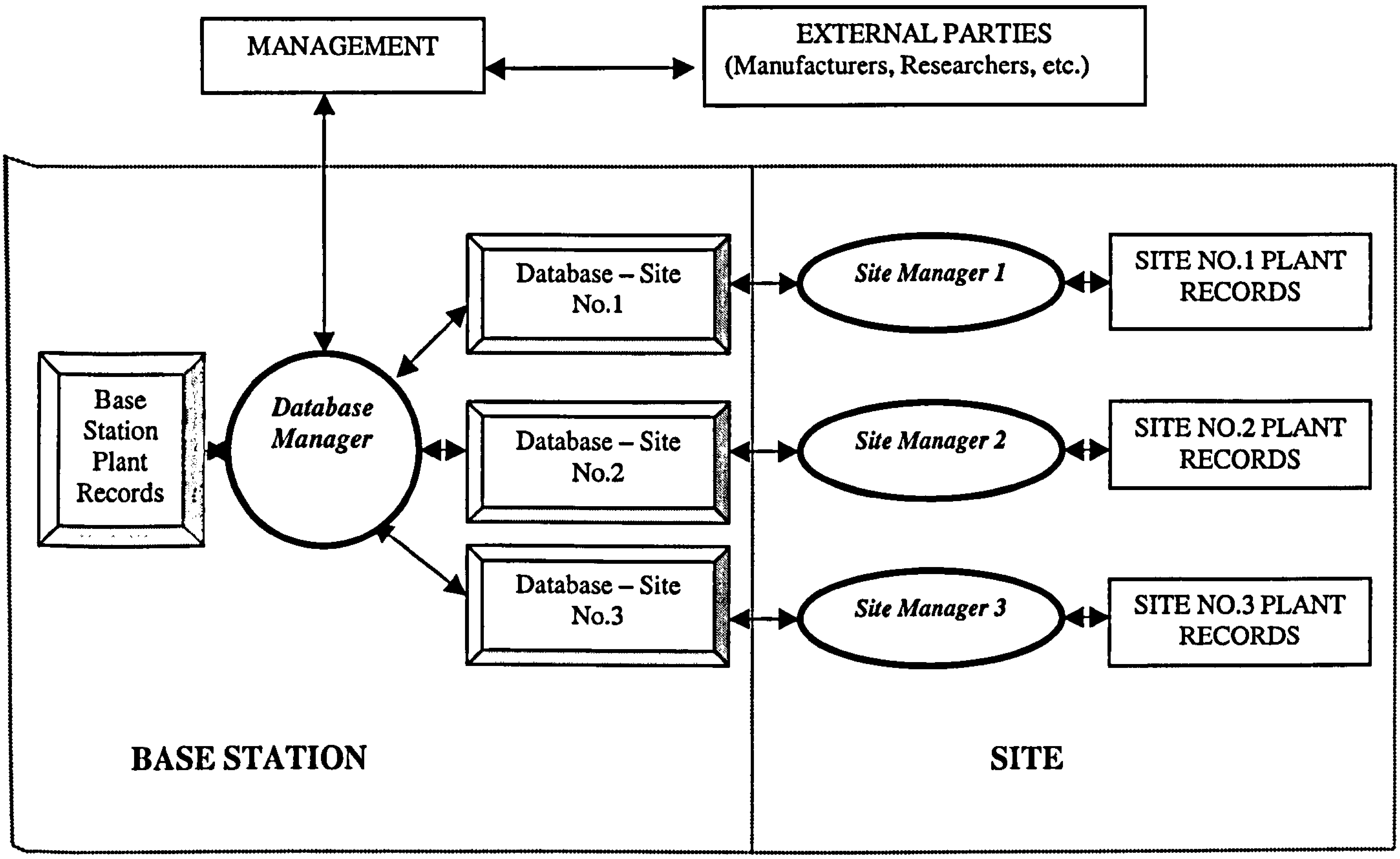
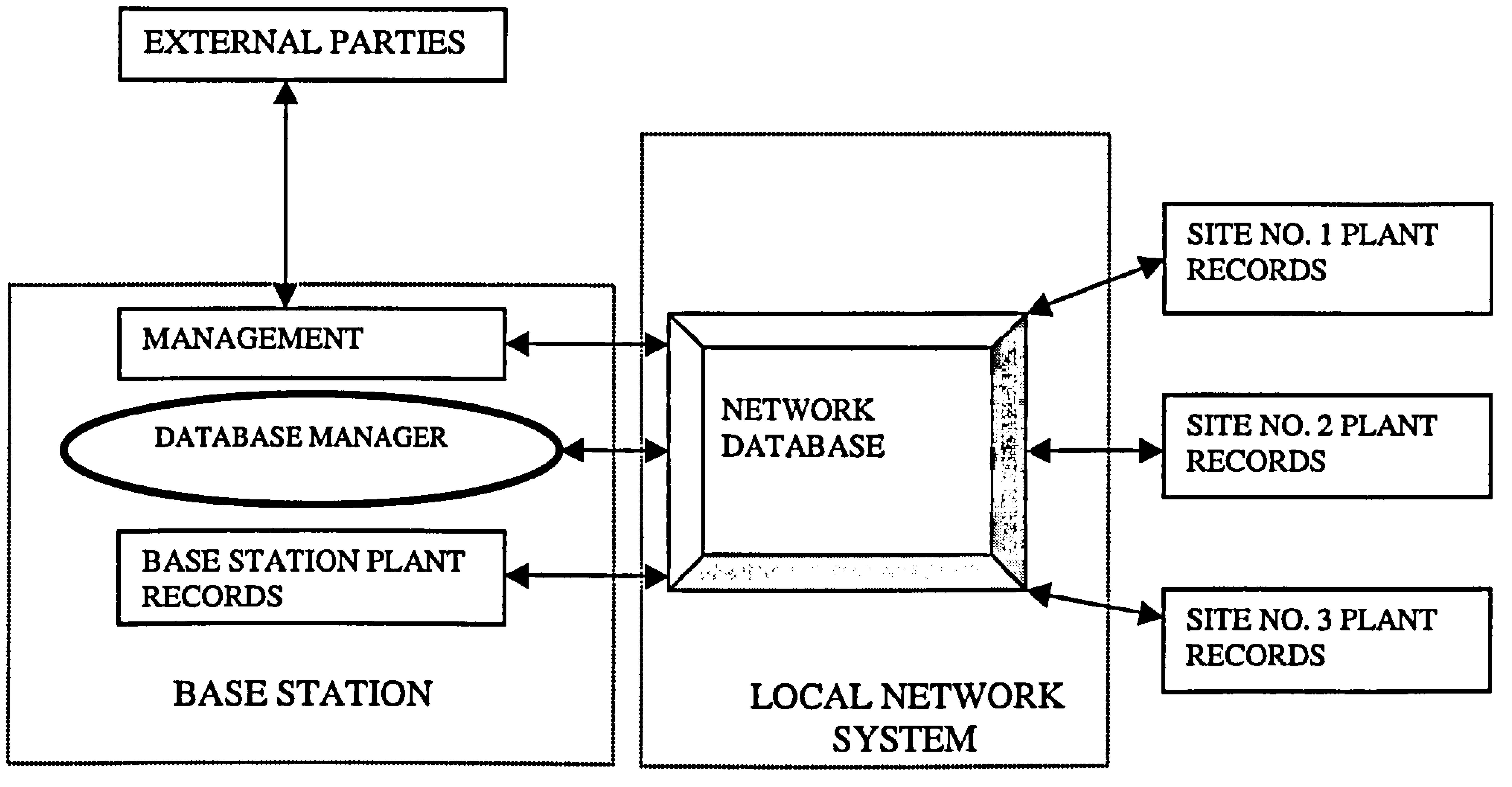


Figure 2.3 presents a typical example of systems under category 2. Essentially, information processing is much better than the single PC 'counterpart' system (as depicted in Figure 2.2), because information bottlenecks associated with over-reliance on the database manager are reduced (Vakola and Rezgui, 2000). Nevertheless, the system still restricts optimal database accessibility from remote locations, particularly for those external to the network. In addition, the capital requirements for linking-up new sites and plant items are usually very high (when compared to Internet based systems).

The recently introduced Internet based plant information management systems (category 3) have largely overcome most of the inherent limitations that exist

Figure 2.3: File Systems and Relational Databases Resident on Local Networks



with the two previous systems described (Felton, 2000). However, an existing limitation is that current Internet based systems produce purely informative data extracted from fixed historical databases (Anon, 2001a). Existing Internet based methods are also based on the use of 'experience' or static models developed from fixed historical records of similar plant items. Two major problems associated with static models based on historical records are:

(i) a failure to account for external factors impacting upon machine performance (e.g. varied site conditions, plant operator efficiency, contractual programmes and so forth) (Wetzel, 1998; Hendrickson, 2000); and

(ii) a tendency to become less reliable over time due to changes associated with plant utilisation (e.g. a reduction in engine efficiency, component wear, effects of downtime, changes in operating conditions and so on) (Lundegard, 1998, Edwards, 1999).

TECHNOLOGY TRANSFER: AN ANALYSIS OF ADVANCED IT APPLICATIONS

Technology transfer can enable the passage of best practise information management practices employed within advanced industries to less advanced industries. An evaluation of existing IT systems in more advanced "mechanical engineering" and similar industries may reveal opportunities for developing an improved off-highway plant information management system. This review considered the aircraft, shipping and railway/road management industries due to IT application advancements made and adopted (Oloke *et al,* 2001). Furthermore, some advanced IT applications for managing information in some engineering applications (such as environmental regulation access, collaborative project management, etc.) were also reviewed.

IT in Aircraft Maintenance Management

Aircraft maintenance management requires the management of a wide range of data such as history records for the different components including installations, repairs and overhauls (Tobin, 1997). Other data include operational hours, cycles and/or months for items designated "on condition" or "condition monitored" and reliability analysis reports (Anon, 2000a). Some private consultancy companies have developed software for aircraft maintenance management over the past two decades (Anon, 2000d). Silicon Wings Inc. (SWI) was the first company in the world to offer microcomputer-based aircraft maintenance software in 1979 (Anon., 2000d). Similarly, AeroInfo builds software for aircraft maintenance planning, scheduling, and tracking (Macdonald, 1999). The company's flagship product, the MAINSTREAM can be deployed very quickly, or accessed over the Internet via application service providers. Other examples of Internet based applications include: Mxi Technologies (Tobin, 1997) and Essential Air (Anon, 2000d).

As a contribution to this literature review, it was observed that IT in the aviation industry has been enhanced significantly particularly, by the adoption of Internet based systems. The Internet based applications have improved the speed in which information is captured, stored and retrieved. Furthermore, other aspects such as cost efficiency, quality control and decision-making have been significantly enhanced (Tobin, 1997; Macdonald, 1999; Anon, 2000d).

IT in Shipping Management

Within the shipping industry, information management often involves the use of a relational database structure both on PC's and on the Internet (Anon, 2000e). EASTREX shipping and Interport's IT systems are prime examples of the many web-enabled software currently being used to enhance inventory control and maintenance data management in this sector of industry.

Interport's information technology system, has Graphical User Interface (GUI) flexibility, a robust/secure client server communication system and extensive automation access. System integrity on the other hand is enhanced by faster performance, standardisation of software and internet/network and database security.

Database security ensures that only authorised users are permitted to access the database. The "IDS web" is an Interport system that enables a registered user (company) to perform the following tasks on-line:

- check fleet inventory in order to monitor details of each ship;
- check the status of any unit regardless of location to facilitate the reporting of maintenance requirements and operational management planning;
- perform real-time estimates of ship parameters that may be required in order to forecast and control costs of operation, maintenance and so on (Anon, 2000e).

The above enhanced information management features are adaptable to off-highway plant. This is because off-highway plant information management also includes inventories, plant maintenance scheduling and the making of operational cost estimates (Boyd, 1995; Wetzel, 1998; Felton, 2000). Therefore, transfer of these advanced information management techniques from the shipping industry to off-highway plant and equipment is achievable.

IT in Railway Information Management

Documentation has been an invaluable asset in large-scale railway companies (Rowley and Butcher, 1998). Furthermore, due to rapid and extensive railway infrastructure developments, documentation has grown tremendously both in terms of diversity and volume (Chan *et al*, 1998). To reduce this documentation build-up, some organisations have developed a simplified and user-friendly documentation formats for launching on intranets (Anon. 2000f). The aim being to download work instructions onto hand-held computers for on-site usage by maintenance staff (Erbschloe, 2001). On-line documents are developed and designed in the Hypertext Markup Language (HTML) format, as web pages for on-line viewing via a browser (Chan *et al*, 1998). This feature could easily be adopted within the off-highway plant sector to distribute management information to geographically dispersed sites.

Similarly, as part of London Underground Limited's business support services, Engineering Information Services (EIS) acts as a custodian for engineering records relating to over 392km of track and hundreds of stations (Anon, 2000f). Beginning in 1992 with a review of their document management requirements, EIS has successfully implemented in stages, the ALTRIS Electronic Document Management. ALTRIS permits up to 1000 users simultaneous access, from any desktop or remote PCs, to hundreds of thousands of documents. The documents range from 19th Century drawings to records of assets built during the new Jubilee Line Extension project (ibid).

In addition to the foregoing, railway information management has also been enhanced by the application of various software. An example is the IRCS (Integrated Railroad Control System) that enables the control all of the functions necessary to operate and manage a short line or regional railroad (Anon, 2000g). This includes maintaining the rail yard and inventory control; transmitting and receiving EDI messages; moving and billing cars; originating and managing waybills; tracking car movement; billing demurrage; and more (Anon, 2000g). The main benefits here include accessibility of information and also the enabling of a 'virtual' collaborative information management environment. Again such features could be transferred to off-highway plant IT packages.

IT in Road Information Management

Road information management has been significantly enhanced by a wide range of IT applications. "At Road Inc.", for instance, is a company that specialises in the provision of productivity enhancement solutions for mobile businesses (Anon, 2000h). Examples of such businesses include courier, taxicab and vehicle charter companies etc. At Road Inc.'s Mobile Resource Management (MRM) gives businesses a competitive advantage through geo-referenced information dissemination. Geo-referencing refers to the ability to locate an object in respect to its real time geographical co-ordinates (Sonuga, *et al*, 2001; 2002). With thousands of subscribers today, MRM gives business location, messaging, reports, maintenance and other productivity enhancement tools. Subscribers can manage their fleets virtually anywhere, 24 hours a day, 7 days a week. The end-to-end MRM solution includes scheduling, dispatching, messaging, location of mobile resources and the delivery of goods and services.

In 1998, the programme FleetASAP was launched as the world's first Internet-based MRM solution. FLeetASAP is a powerful turnkey solution providing the following vehicle operational parameters: location information; dispatch applications; work metric status, activity and messaging history reports; instant 2-way wireless messaging solutions; and intelligent scheduled maintenance (Anon, 2000h). This development generally improved mobile asset management by providing a means for users to acquire robust control of their fleet from geographically varied locations. The main benefit of this system is the ease with which fleet operations and maintenance management could be conducted. In particular the intelligent scheduled maintenance enabled the enforcement of routine preventive maintenance programmes.

OTHER RECENT DEVELOPMENTS IN ENGINEERING INFORMATION MANAGEMENT

Web-based database applications are rapidly being embraced in the various engineering disciplines (e.g. building design and construction, site redevelopment, and industrial operations, etc.) (Hinks *et al*, 2000; Erbschloe, 2001; Anumba *et al*, 2002). For example, many engineering activities are governed by environmental regulations that are constantly being revised and published (Abdou, 2000). In response to these ephemeral changes, many U.S environmental protection agencies are now using Web sites to provide access to their regulations. However, recent research observed that many of the initially developed regulatory agency Web sites provided no support, other than browsing, for finding relevant regulations (Liang and Garret, 2000). To resolve this problem, a java-based environmental regulation broker was designed to help users locate relevant environmental regulations. The rationale for the development was that eventually, such broker software could be provided by regulatory agencies as a standardised support to provide a faster and easier access to their regulations over the Internet (ibid).

Web-based Collaborative Project Management

A concerted effort has been made by various practitioners and academics in the construction sector to adopt web-enabled technologies (Scott *et al*, 1998; Sun *et al*, 1999; Hinks *et al*, 2000). Some of these initiatives include:

i) the development of an Internet-based Intelligent system for project management. The system utilises data from historical projects to model project performance. This is from a management point of view, which evaluates performance line with established key performance indicators (KPIs) (Scott *et al*, 1998);

ii) the establishment of an intelligent agent based collaborative construction information network which supports collaborative information searching and retrieval for construction related topics on Intranets and the Internet (Sun *et al*, 1999); and

iii) the utilisation of the Internet for enhanced knowledge management in the construction industry (Hinks *et al*, 2000).

In addition to the above and as a major milestone, the concept of collaborative project management using web-based technologies has blossomed and today, over 150 collaborative web-based solutions exist for project management (Abdou, 2000; Erbschloe, 2001; Anon, 2001b). Typically these applications use a web browser on a client computer to run the programme residing on the server (Faraj *et al*, 1999). The entire processing is carried out on the server as if it were at the user's local machine (Chen and Heath, 2001). Some typical examples of the web based collaborative project management tools are:

- 1workgroup.com – represents an engineering industry's web-based application service committed to solving the problem of interoperability among CAD/CAM/CAE applications. The application automatically translates 3D models so as to make them compatible in multiple engineering processes (Anon 2001c).
- The powertool.com – this is an Internet structured and browser-based software application that provides better communication, collaboration, document management and tracking for industry (Anon 2001d).
- Blueprint online – this is an Internet based application that compiles a project database and enables an on-line access to a wide number of attributes related to every individual project (Anon 2001e).
- Constructionbidding.com – this allows the viewing on-line of project status thereby allowing the management of project documents on line in a secure environment (Anon 2001f).
- Bricksnet – this service allows the sharing of project drawings and other technical images over the web (Anon 2001g).
- Novient e-services – this is a leading software application for service process optimisation. The Internet-based solutions offered allow on-line data management, resource management, project collaboration, knowledge management, time and expense data and performance management (Anon 2001h).

The above examples are merely a representative sample of the range of solutions offered by existing web-based collaborative management tools. Many more do exist.

AN EXPLORATION OF IT APPLICATIONS IN OFF-HIGHWAY PLANT MANAGEMENT

Rapid technological developments in computer technology coupled with 'user-friendly breakthroughs' (made during the last decade) have facilitated a boom in IT applications applied within the off-highway industry. Advancements such as the evolution of graphical user-interfaces, networking and communications are good examples (Benfield, 2000). Various Governments have also initiated programmes aimed at encouraging the use of IT in construction (Anon, 2000c).

Over the last few decades, computers have assisted in almost all aspects of management within the off-highway industry (Barton, 1985). Typical areas of application include: estimating, scheduling, operations simulation, safety, structural analysis and data collection and robotics (Boyd, 1995). Generally, most applications fall under data management and administration and automated data acquisition and process control.

The fundamental components of information management systems are databases that enable systematic collecting, storing and quick utilisation of data (Baldwin, *et al*, 2000; Bertino *et al*, 2001). Such data are important for business activities and may be expressed either in Figures, text or as a drawing (Maxwell, 1991).

Historical databases are useful tools for capturing and sharing data on a wide range of operations in project management (Thorpe, *et al*, 1995; Canter, 1993, Boyd, 1995). These data include:

i) quantities and unit rates of paid work for completed projects;

ii) consumption of labour, plant/equipment and materials and overall financial effects on projects;

iii) equipment functioning, for example, statistical data on the average periods of operation and failures;

iv) estimation of plant/equipment periods of production/transportation/installation, trial runs and warranty periods;

v) personnel involvement on a specific project and the respective output; and

vi) sub-contractors and influential individuals among the sub-contactors whose decisions might affect the business activities.

The myriad of capabilities inherent within databases enhances the ease of collating and reporting performance and productivity (Edwards *et al*, 2002). Databases also provide a quick means by which management can readily assess their organisation's performance over time (Nunnally, 2000; Becker, 2001).

File Management Systems in the Off-Highway Plant Sector

Equipment file management software are utilised in a number of different ways. Files include: maintaining ownership and utilisation status records (Canter, 1993; Felton, 2000); computing ownership and operating costs (Edwards, 1998); dispatching maintenance (Gerold, 1997; Nunnally, 2000); and economic policy studies (Edwards *et al*, 2002). These files significantly enhance plant and equipment data management. This is because the volume of data within individual files usually requires computerisation. Computerisation is usually required due to the lengthy and cumbersome nature of manual manipulation (Maxwell, 1991). In general, key benefits of a file management system for plant information management includes: ease of data manipulation and analysis and quick retrieval of any data relating to a specific item of plant through the use of the plant ID number (Edwards, *et al*, 1998). In addition, the system will also automate production of plant template forms, e.g. machine cost estimation sheet. The culmination of these palpable benefits is reduced administration costs and enhanced quality of information.

Applications of file-management systems can also improve the management of materials and equipment inventories (Baldwin *et al*, 1995). This is achieved by enhancing the management of the general records system. The file system utilisation consists of: the design of records, data-entry screens, output reports and data management options; the data entry process; the searching, selecting and sorting information and the preparation of various reports (Canter, 1993; Aouad and Sun, 1999). Furthermore, there can also be options for exporting and importing data to and from other applications.

Relational Database Management Systems

Relational database-management systems (RDBMS) provide the capability to build integrated applications that draw upon the equivalent of multiple files (Chen *et al*, 1994; Becker, 2001). 'Relational' is the dominant technology for new databases due to their capabilities for ensuring data integrity of the after periodic updates (Carter, 2000; Bertino *et al*, 2001). The concept deviates from existing file systems or earlier database architectures through the enforcement of referential integrity. Referential integrity safeguards the duplication of data entry within related database tables (Zhang, 1999). Consequently, RDBMS permits the development of several different linked record layouts, additional data entry screens, reports, extensive programmability and access to selected data residing on the Internet (Turban and Aronson, 2001; Chipman and Baron, 2001). Several DOS/Windows-based file management/ database applications currently exist. Examples are Microsoft Access and Visual Basic Applications (VBA), Oracle8 with SQL/PL applications, dBase VII, etc. (Prothman, 1999; Becker, 2001).

The capabilities of database management applications facilitate the electronic storage and management of data. Unlike spreadsheet applications, they enable the data to be viewed and extensively queried for report generation. Also, forms can easily be modified as often as required. Other advanced features include:

i) data storage protection and security;

ii) on-line help for ease of operating the systems;

iii) arithmetic computation or provision of direct link to mathematical models that compute summations, products, averages and other relational algebra operations;

iv) graphics that simplify report presentation;

v) programmable macro commands that aid the development of forms and reports from database queries; and

vi) network data access, which facilitates the ease of data update on the database and the generation of reports by various departments and managerial levels.

COMPARATIVE ANALYSIS/REVIEW

This review has enabled a compilation and assessment of advanced IT applications in technologically advanced industries (aviation, shipping, railway and road). In addition, a review of recent advancements in information management in other engineering disciplines was also made. A number of interesting issues arise from the other industries and sectors reviewed under this study. These range from the utilisation of the Internet for fleet documentation and management to the stringent fleet inventory and monitoring programmes by advanced industries. Throughout these industries, these advancements have enabled:

- fleet inventories to be monitored and managed efficiently and effectively (Chan *et al*, 1998; Anon, 2000e; Anon, 2000h);
- real-time estimates of various performance fleet and individual unit parameters to be made (Anon, 2000d; Anon, 2000f; Anon, 2000h);
- intelligent scheduled maintenance to be carried out(Anon, 2000g; Anon, 2000h);
- shared working environments to be facilitated (Abdou, 2000; Erbschloe, 2001; Anon, 2001b);
- project status to be monitored (Anon, 2000g); and
- fleet and overall project performance to be monitored against KPIs (Scott *et al*, 1998; Anon, 2000h).
- efficient on-line machine monitoring: other industries reviewed (especially aviation and shipping) monitor machines on-line unlike off-highway plant, which 'tends' to be monitored periodically even when using predictive

technologies such as Used Oil Analysis (UOA) (MacDonald, 1999; Edwards, 1999).

Figure 2.4 illustrates a summary of comparisons between the above industries, indicating areas where further IT application development is required. The Figure is based on the major uses of the Internet in plant maintenance information management (Levitt, 1998). The results reveal that whilst the aviation, shipping, railway and road industries have adopted Internet based solutions to information management, the off-highway plant sector has failed to fully integrate Internet capabilities into current information management systems employed.

Figure 2.4: Comparative Analysis of Existing Internet-based IT Applications

		INDUSTRY			
S/No.	APPLICATION	AVN	SHP	RRD	OHP
1	E-mail	**	**	**	*
2	Finding vendors	**	**	**	**
3	Technical bulletins	**	**	**	**
4	Drawings, field modifications, manuals	**	*	**	*
5	Commerce	**	**	**	**
6	Web-based intelligent system	**	**	**	*
7	Web-based report sheets	**	**	**	*
8	Technical help	**	**	**	**
9	Software changes	**	**	**	**
10	Directories of installers and vendors	**	**	**	**
11	User groups	**	**	*	**
12	Frequently Asked Questions (FAQs)	*	**	*	**

Key:

AVN – Aviation
SHP – Shipping
RRD – Railway and roads
OHP – Off highway plant
** - Application is currently being utilised
* - Application is currently under-utilised

SUMMARY

Traditional paper, file and database systems have been used extensively in the off-highway plant sector over the last few decades (Barton, 1985; Maxwell, 1991; McCaffer and Thorpe, 1992; Boyd, 1995). These methodologies have assisted in the management of plant history information by enabling a process whereby historical data may be retrieved and evaluated from time-to-time (Edwards *et al*, 2002).

However, the three categories of plant information management systems currently in existence do not have the capacity to adequately support the dynamic requirements of modern off-highway plant information management (Edwards *et al*, 1998; Lundegard, 1998; Nunnally, 2000; Oloke *et al*, 2001). Several limitations account for this inadequacy, four of these are most notable. First, the systems are not easily accessible from remote plant locations. Second, there is an over reliance on the database manager. Third, the reports generated often require lengthy mathematical manipulations. Fourth, the existing Internet based systems are mostly informative in nature.

A review of advanced IT applications in industries such as aircraft, shipping, railways and road information management has been made. Findings reveal that these industries have adopted intelligent web-based information management technologies that significantly enhanced their operations. These web-based systems reduce problems of accessibility to the system and therefore allow ease of database update. The application of web-based tools for information management also enhances the up-to-the minute project information retrieval by teams composed of geographically dispersed individuals (Abdou, 2000; Liang and Garret, 2000). Hence, the use of web-

based technology means that the application can be managed from one-central location (Pavlunusic and Lovrencic, 1999; Dillinger, 2000). These attributes facilitate the application of these tools for intelligent decision support. When compared with the off-highway plant sector, these other industries were observed to be more advanced in terms of information management. For example, about 150 web-based tools currently exist for collaborative project information management in construction. However, none of these have been specifically designed for plant information management. The need to develop an intelligent web-based tool for off-highway plant is, therefore, further reinforced.

CHAPTER THREE: Intelligent Web-based Information Management System: Theoretical Concepts

INTRODUCTION

Intelligent web-based systems are based on the paradigm of decision support provided by PC based intelligent decision support systems (Famili *et al*, 1996; Zhang, 1999; Guohua, 2000). The application of web-based tools, in the utilisation of the systems, enhances the up-to-the minute project information retrieval by teams composed of geographically dispersed project participants (Abdou, 2000; Liang and Garret, 2000). A prerequisite requirement of any intelligent web-based system is that it is both effective and sustainable (Sugumaran and Storey, 2000; Turban and Aronson, 2001; Anumba *et al*, 2002). Hence, it is necessary to evaluate the requirements for various resources required to build such systems (Dillinger, 2000; Erbschloe, 2001). Resources include: personnel/labour skills; time; money; and facilities such as software, hardware, tools, equipment, etc. These are usually needed at most stages of the system development. INTELLIPLANT was conceptualised as an intelligent web-based system that seeks to improve off-highway plant information management. The development of INTELLIPLANT has therefore been based on an extensive evaluation of the aforementioned resources.

For INTELLIPLANT's development, a logical theoretical framework was formulated. This framework consisted of the required component system elements for the system (e.g. the data capture and the model base systems) (Aouad and Sun, 1999). The framework development process was based on a literature review of intelligent web-based information management systems. This review commenced with an appraisal of a strategic approach required for planning and developing web-based systems. Sequel to this, fundamental theories underlying the typical systems were evaluated. Theoretical evaluations included a review of the required system architecture and detail component structure.

WEB-BASED INTELLIGENT MANAGEMENT SYSTEMS

The planning and development of web-based systems requires the implementation of a formal strategic approach (Zhang, 1999). According to Clyde (2000), a formal strategic approach visualises the system development process as a continuous loop of activities that guarantees efficiency. An illustration of the approach is shown in Figure 3.1. This approach covers the development process from the time that the original planning question – 'Should we have a web-based system?" – is asked, through all the planning phases from the establishment of the system to its on-going operation and evaluation. It also relates it to the cycles of other aspects of an organisation's planning (Greenspun, 1999). It also provides a basis for the consideration of issues that are important at each stage of the process (Clyde, 2000).

A web-application is based on a collection of individual web pages (Dillinger, 2000; Sugumaran and Storey, 2000). This enables the division of applications into clearly demarcated sections, allowing or denying access as needed (Faraj *et al*, 1999). Figure 3.2 illustrates the layout of a typical web application. Each page can include an appropriate user interface for gathering and displaying data, help directories, etc. Generally, the use of web-based technology means that the application can be managed from one-central location (Pavlunusic and Lovrencic, 1999; Dillinger, 2000). Carefully selecting the system architecture is thus an essential step towards ensuring the maximum efficiency of the web-based system (Prothman, 1999; Greenspun, 1999).

Figure 3.1: Strategic Planning/Development Cycle for a Web-based System

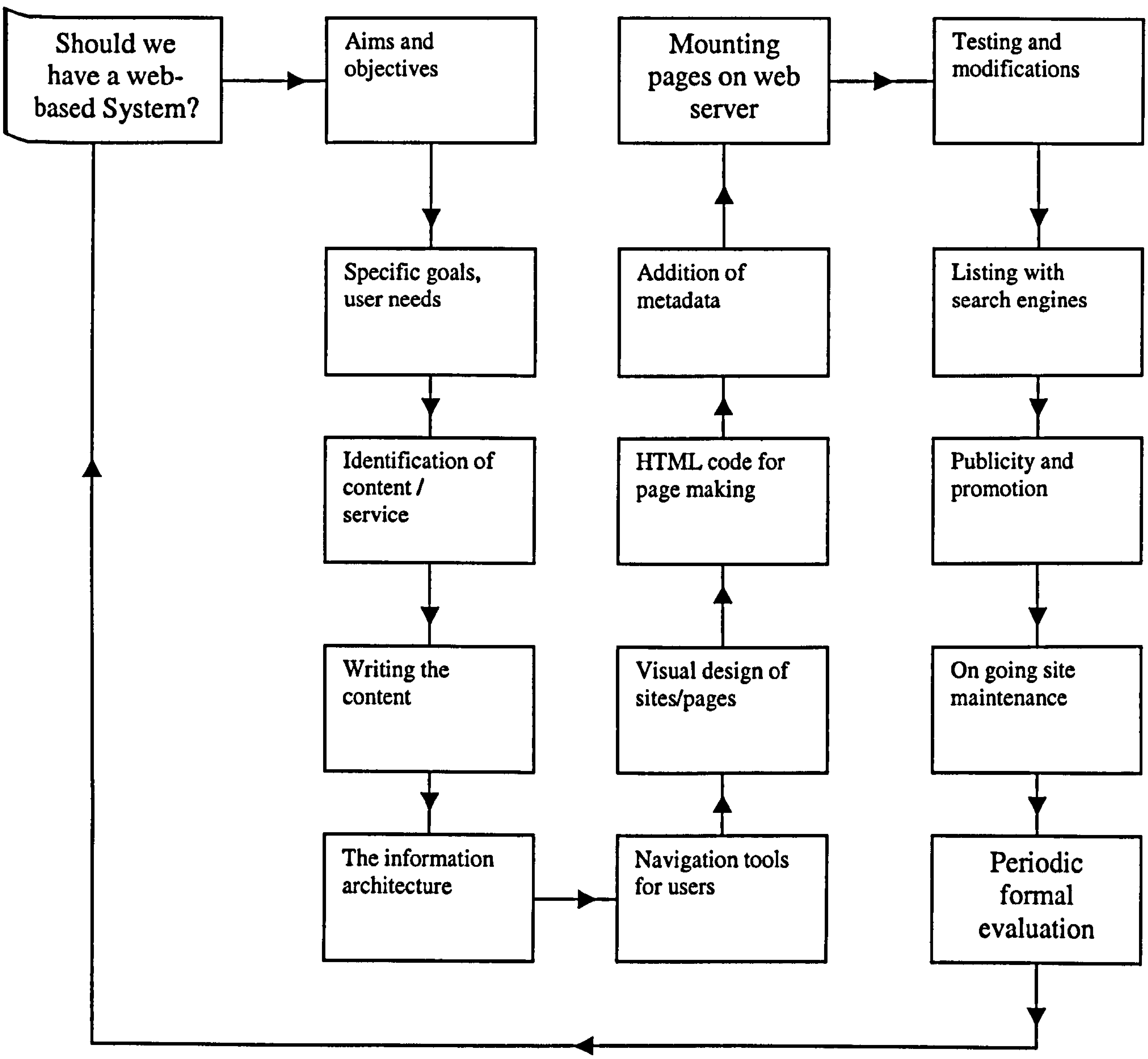
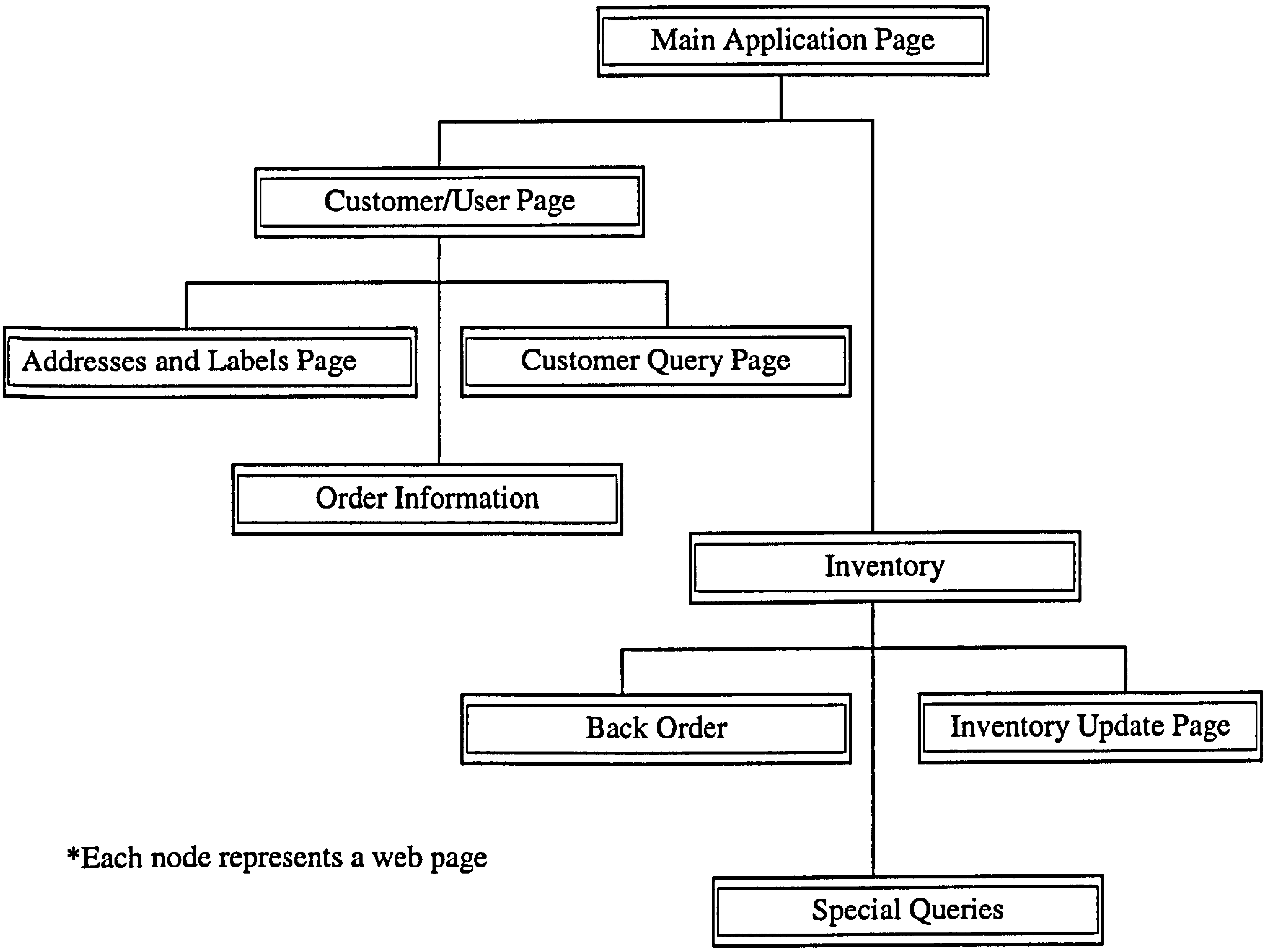


Figure 3.2: The Layout of a Typical Web Application



Components of Intelligent Web Based Systems

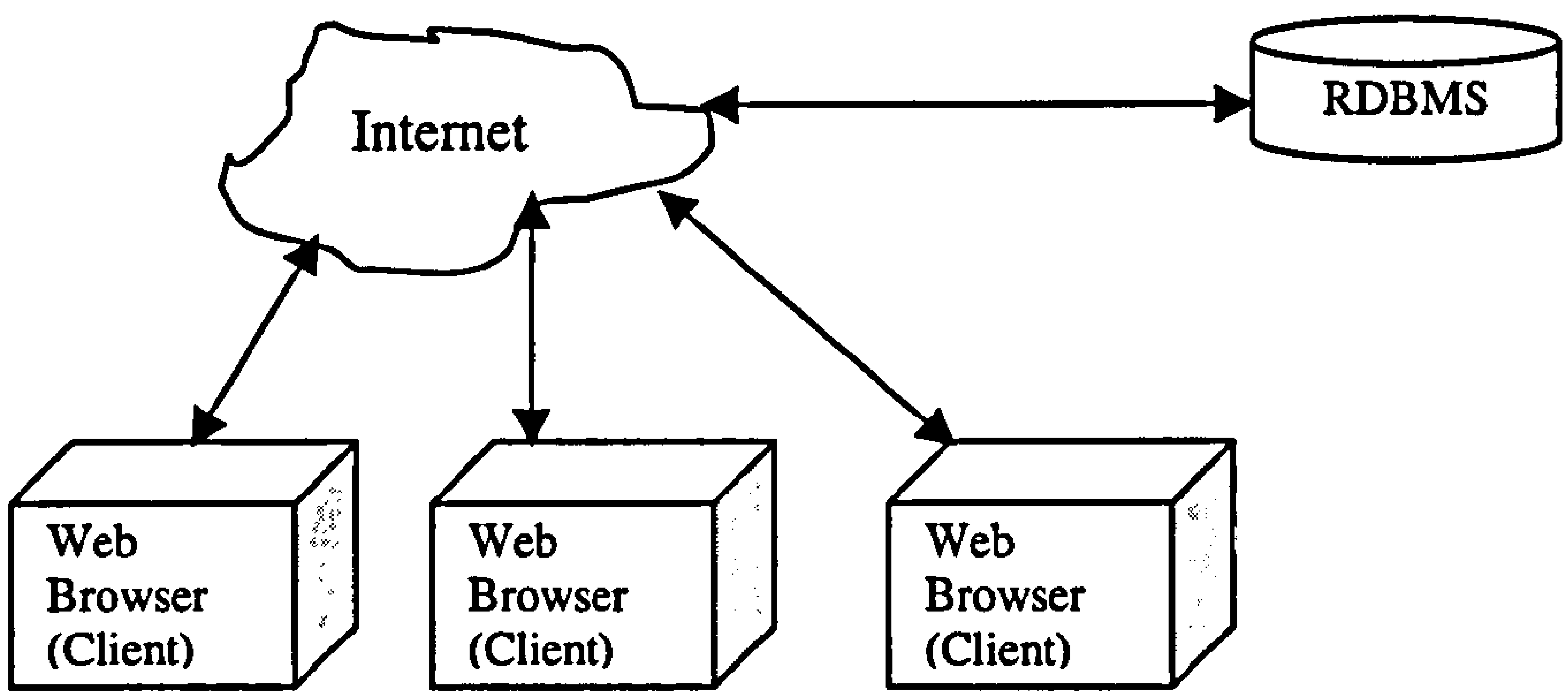
There are two major options for the architectural design of web-based intelligent systems namely the two and three-tier client server architectures (Greenspun, 1999; Dillinger, 2000). Although each system has its unique advantages, three-tier web based client-server architectures have been proven to provide a suitable hosting platform for most intelligent systems (Sun *et al*, 1999; Liang and Garret, 2000; Chipman and Baron, 2001). The first tier hosts the user interface and runs on the client's machine. The second tier is a broker server that is designed as a Java, Hypertext Mark-up Language (HTML) or Common Gateway Interface (CGI) Scriptenabled Open Source Database Connectivity (ODBC) sub-system (Liang and Garret, 2000). The second tier resides on the web server and enables communications between the first and third tiers. The 'intelligent' components are made resident on the third tier of the system. This third tier comprises of a web-enabled Relational Database Management System (RDBMS), a Model Base Management System (MBMS) and an interface with Knowledge Base Management System (KBMS) (Bertino *et al*, 2001). The theoretical concepts behind all the components are hereby briefly described to facilitate a holistic understanding.

The Web-Enabled RDBMS

Database engines can exist as simple text files or be expanded up to a relational database such as those developed by Oracle, Borland, Sybase and Microsoft (Pavlinusic and Lovrencic, 1999). Figure 3.3 illustrates the basic components that must be contained within a web-enabled RDBMS application. This illustrative diagrammatic representation reveals that an application server performs most of the application processing logic and enforces business rules (Baron and Chipman, 2001). Such rules include access services, query responses and so forth. The RDBMS is designed to supplement the standard operating systems by allowing for greater data integration, complex file structure, quick retrieval and changes and better security (Turban and Aronson, 2001).

Figure 3.3: Components of a Web RDBMS Application

(Source: Greenspun, 1999)



Off-highway plant history data (such as inventory, maintenance, fault logging, etc.) dynamically change at an almost exponential rate (Edwards, *et al* 1998; Anon, 1999a) as a result of changes in projects' physical and environmental factors (Hendrickson, 2000). In addition to the problem of estimating these environmental factors, it may also be important to account for interactions among the factors and also the exact influence of particular site characteristics (ibid).

The capture of off-highway plant history data thus requires a system that can allow multiple accesses for update and queries; therefore, a RDBMS is most suitable (Turban and Aronson, 2001). Furthermore, a RDBMS has a unique advantage over other database structures such as the: hierarchical, network, object-oriented, multimedia-based database systems. This is because it greatly facilitates the dynamic modelling of a non-static database (Scott *et al*, 1998; Zhang, 1999; Pavlinusic, *et al* 1999). It also allows for dynamic updates of historical records based on the newest records through the enforcement of referential integrity (Carter, 2000; Becker, 2001).

This characteristic is most useful to the development of dynamic modelling of historical records (Anon, 1999a). In addition, a web-enabled database is integrated into an Internet server and allows users to retrieve information from the web, query and process data through the Internet using only a web browser and standard desktop hardware (Greenspum, 1999; Prothman, 1999; Anon, 1999b).

The MBMS

A model base contains routine and special statistical, financial, forecasting, management science and other quantitative models that provide the analysis capabilities in a decision support system (Turban and Aronson, 1998). The MBMS represents a platform that hosts dynamic models that enable the prediction of salient parameters such as plant breakdown, maintenance costs, etc. The following are desirable capabilities of an MBMS (Scott *et al*, 1998; Turban and Aronson, 1998):

i) control – the system should support both fully automated and manual selection of models that are useful to users;

ii) flexibility – users should be able to develop a solution using a combination of modelling approaches;

iii) feedback – the MBMS should provide sufficient feedback to enable users to access the problem-solving process at any time;

iv) interface - input system requirements should be minimal and users should be able to access desired models within the MBMS with relative ease;

v) redundancy reduction – the MBMS should maximise the use of shared models and associated elimination of redundant storage; and

vi) increased consistency – the system should possess the ability to allow multiple decision makers to simultaneously utilise the same model .

Model development procedure for a MBMS is usually based on analysis using deterministic methods (Edwards *et al* 2001; Guohua, 2000). Thereafter, the ability to invoke, run, change, combine and inspect models are key elements of an intelligent system (Pavlinusic and Lovrencic, 1999). The MBMS is therefore designed to interrelate with the historical data contained within the RDBMS. The major functions of the MBMS are its ability to create and manipulate models easily, to its ability to access and integrate model building blocks (Turban and Aronson, 1998; Zhang, 1999). The MBMS of an intelligent system is typically composed of the following elements (Figure 3.4):

i) model base – a listing of all models that could be used for predicting future parameters based on the historical records contained in the database;

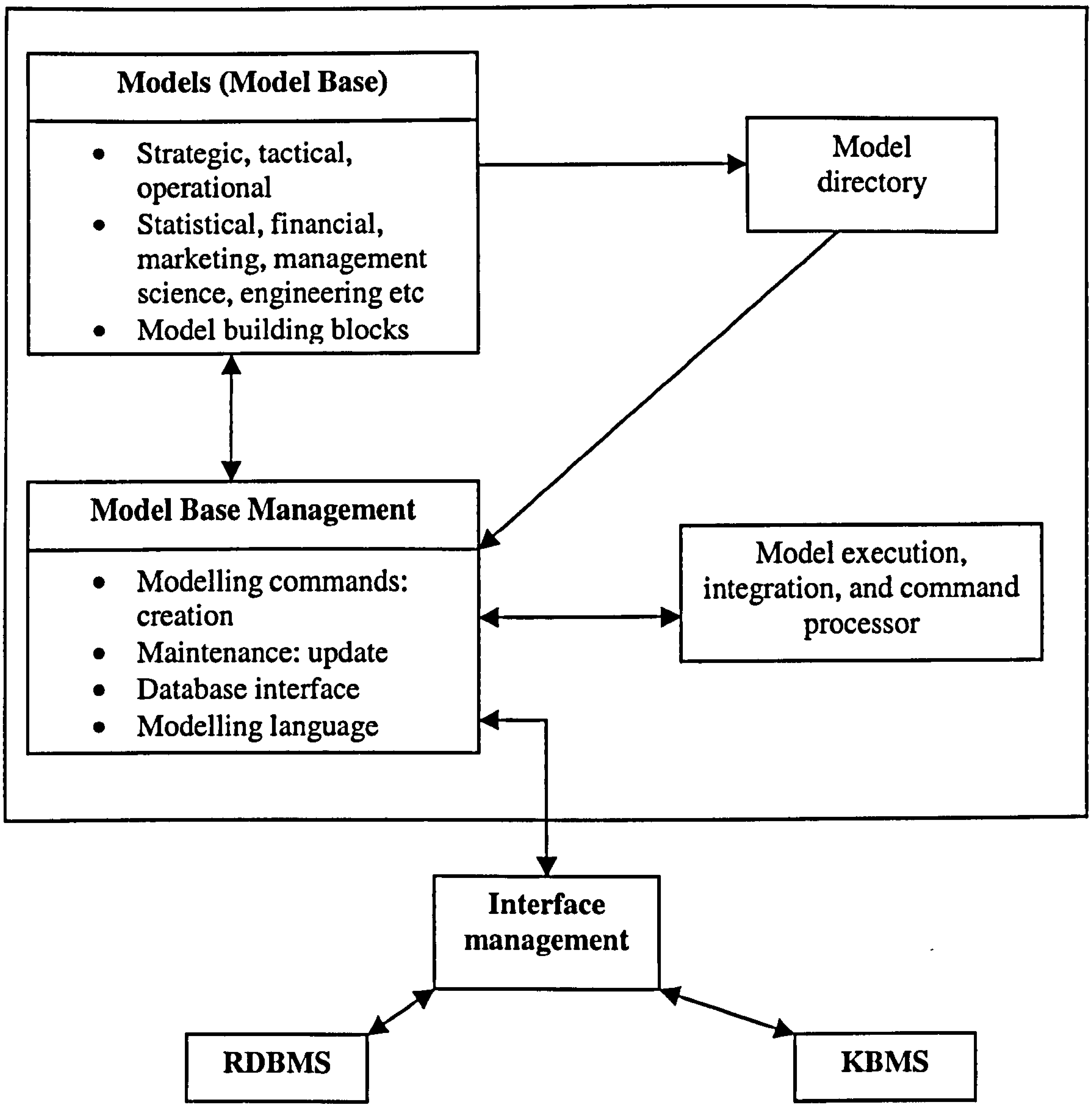
ii) model base management sub-component – an inter-phase technology that enables the MBMS to communicate effectively with the RDBMS;

iii) modelling language – programme languages that engender the functionality of the models within the MBMS;

iv) model directory - an indexing system that allows users to extract required models at any given time; and

v) model execution, integration and command processor – the output inter-phase that facilitates the generation of reports from the model base.

Figure 3.4: The Structure of the Model Base Management System
(Turban and Aronson, 1995)



The KBMS

Data consists of facts and Figures that are relatively meaningless to the user (Rowley and Butcher, 1998). Information is data that have been shaped or formed by humans into a meaningful and useful form (ibid). Knowledge is the stock of conceptual tools and categories used by humans to create, collect, store and share information (Egbu, 2000). When data is processed, it can be converted into information. Likewise, when information is processed, it can provide knowledge (Baek *et al*, 1997). To create knowledge in organisations, managers must manage the processes that transform data into knowledge efficiently and effectively (Hoven, 2001).

Knowledge management (KM) is strongly rooted in the discipline of Knowledge Engineering (KE), which evolved out of the Artificial Intelligence (AI) field (Berka, 1997). KM is based on the representation of experience as cases, which have attributes to categorise them. Like data and model management, knowledge management can also provide the necessary execution and integration of the intelligent system (Turban and Aronson, 2001). Three major approaches may be used to establish a KM tool (Timar, 1999). These are: rule based, case based and tacit rule based reasoning.

Rule Based Reasoning

In the rule based reasoning approach, attributes can be subordinated to each other and any of them can be selected to depend on others. The reasoning (decision) function activates these rules and knowledge is subsequently generated (Egbu, 2000). For example, a recent related study utilised the rule-based technique to produce a conceptual knowledge representation model for construction plant maintenance cost assessment (Oloke and Edwards, 2002a). The relationship between maintenance cost factors, total maintenance cost and its consequences were established using fuzzy association and fuzzy composition (Baek *et al*, 1997). In addition, a double premise rule was used to represent the relationship between the likelihood of occurrence, L; the magnitude, G; and the effect of a maintenance cost factor, C such that

$$\text{if L and G then C} \tag{4.3}$$

Depending on the number of maintenance cost factors being considered, many of the above relationships would exist with varying values of L, G and C. Fuzzy associative memories (FAMS) may thus further be used to represent the relationships. Hence, two FAM matrices, M_{LC} and M_{GC}, may be assembled to relate each premise to the conclusion (Tah and Carr, 2001). So if a maintenance cost factor has a likelihood of L* and a magnitude of G*, the effect or induced fuzzy set on C can be independently determined through composition thus;

$$L^* \circ M_{LC} = C_L^* \tag{4.4}$$

$$G^* \circ M_{GC} = C_G^* \tag{4.5}$$

These may then be recomposed using the fuzzy logic intersection operator such that

$$C^* = C_L^* \wedge C_G^* \tag{4.6}$$

Equation (4) gives the effect C* for an individual FAM. In the event that there are m rules, the total effect C of these rules is simply the fuzzy union of the resultant magnitude fuzzy sets (Turban and Aronson, 2001). Therefore:

$$C = C1^* \cup C2^* \cup \ldots\ldots Cm^* \tag{4.7}$$

In (4.7), the value of C = effect for a given maintenance cost factor with a defined likelihood and magnitude.

Based on the above, the rule-based system utilises the conventional fuzzy technique for calculating the total effect C on a total plant maintenance cost T, which is influenced by n maintenance cost factors. This is by the aggregation of the effect of all the cost factors using a fuzzy union operator as in (4.7).

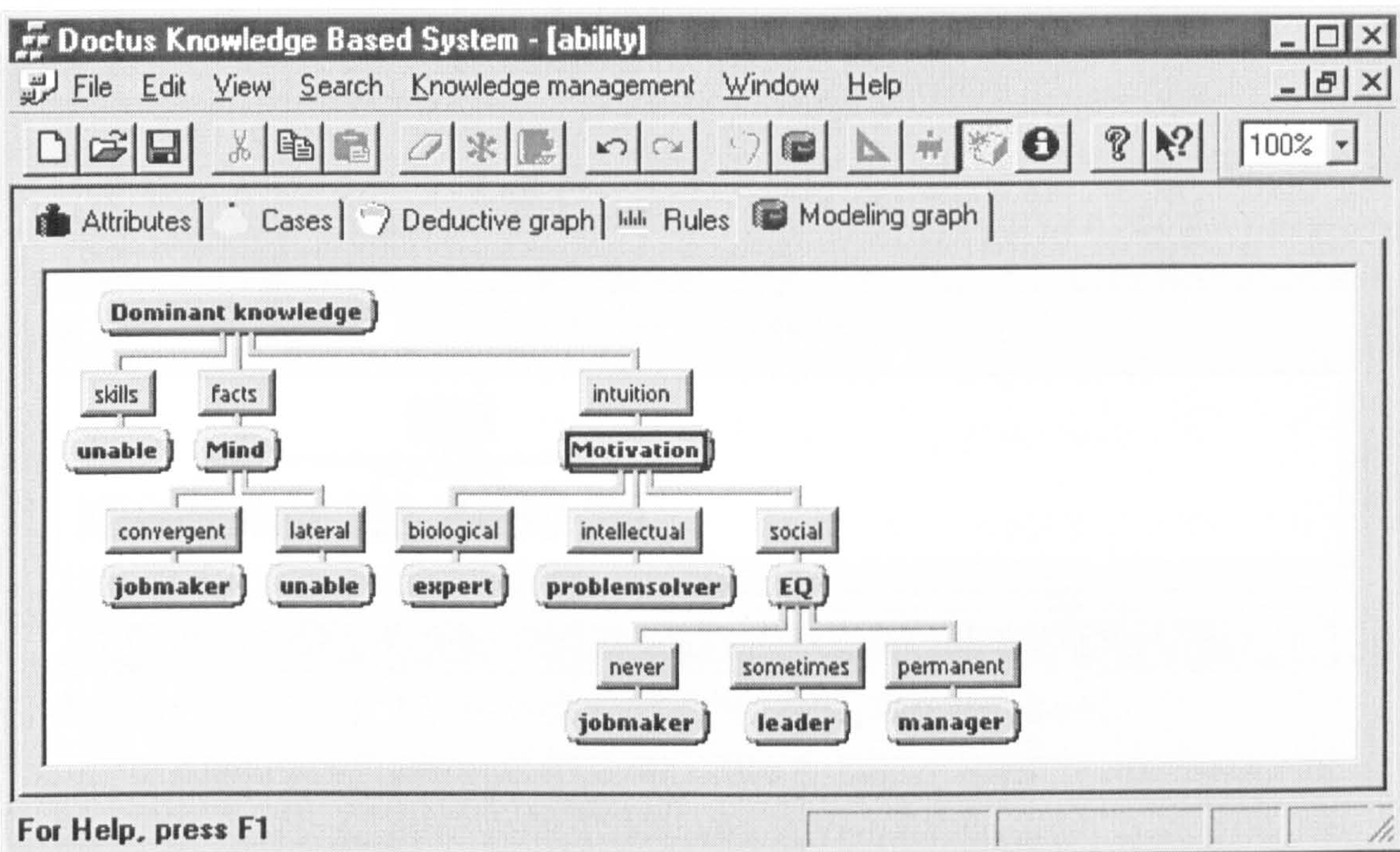
Case Based Reasoning

In this approach, an algorithm based on informativity computing selects the most informative attribute and organises them in a graphical manner (Klein and Methlie; 1995; Timar, 1999). For example if, for a few dozen cases, the majority of attributes are known, then one can be singled out as the qualifying attribute (benchmark). The algorithm then uses this benchmark attribute to rank the others in a graphical manner. As illustrated in Figure 3.5, this graph models the benchmark of cases. The graph shown was generated using the Doctus KBMS to illustrate this approach. The Doctus system has the capability of representing attributes as viewpoints.

The following rule is effective for all the cases shown in Figure 3.5: if "knowledge" is "intuitive" and "motivation" is "intellectual", then the "skill" lies in "problem solving" (Baek *et al*, 1998).

The method involves accessing problem-solving experiences (cases) and inferring solutions for solving future problems. Therefore, the collection of the historical cases and their resolutions constitutes a knowledge base (Timar, 1999). The decision maker recalls previous cases, which may be identical to the new ones but usually are not. They may exhibit only slight hints of similarity with a new case but even such hints may be useful. Knowledge acquisition is simple because the historical data are on file and only minor verifications with experts may be needed (Turban and Aronson, 2001).

Figure 3.5: Case Based Reasoning (Timar, 1999)

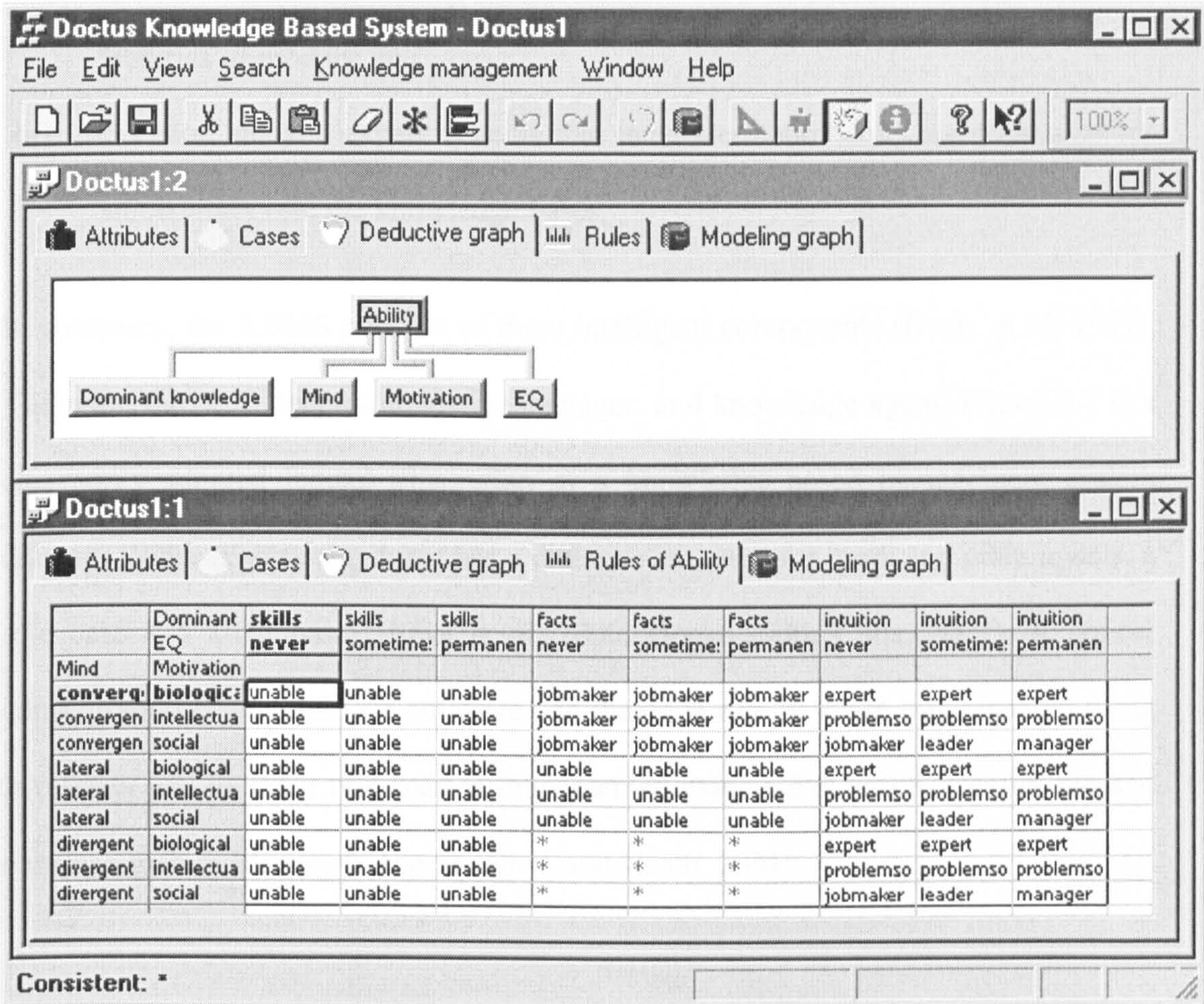


Tacit Rule Based Reasoning (Inductive Reasoning)

Tacit rule based reasoning is a extended form of case based reasoning (Egbu, 2001). The tacit approach involves a procedure in which opinions may be formulated on further cases based on tacit rules (Klien and Methlie, 1995). It is also called inductive reasoning (Figure 3.6). Using the model illustrated above, the tacit based knowledge base can be formulated as shown in Figure 3.6.

With tacit rule based reasoning, the resulting representations and search strategies enable the encoding of real world situations (Luger and Stubblefield, 1998). When a case library is large, a hierarchical re-organisation of the case into smaller sub-sets facilitates retrieval (Kolonder, 1993). The tacit reasoning approach generally looks for similarities over a series of instances and form categories based on those similarities (Klien and Methlie, 1995; Timar, 1999).

Figure 3.6: Tacit Based Reasoning (Timar, 1999)



The Functions of the KBMS

A KBMS is a computer programme containing organised knowledge, both factual and heuristic. It concerns some specific areas of human expertise and is able to produce user inference (Timar, 1999; Zhang, 1999; Liang and Garret, 2000). Silverman (1995) suggests three ways for knowledge-based expert systems to be integrated with mathematical modelling:

i) knowledge-based decision aids that support the steps of the decision process undressed by mathematics;

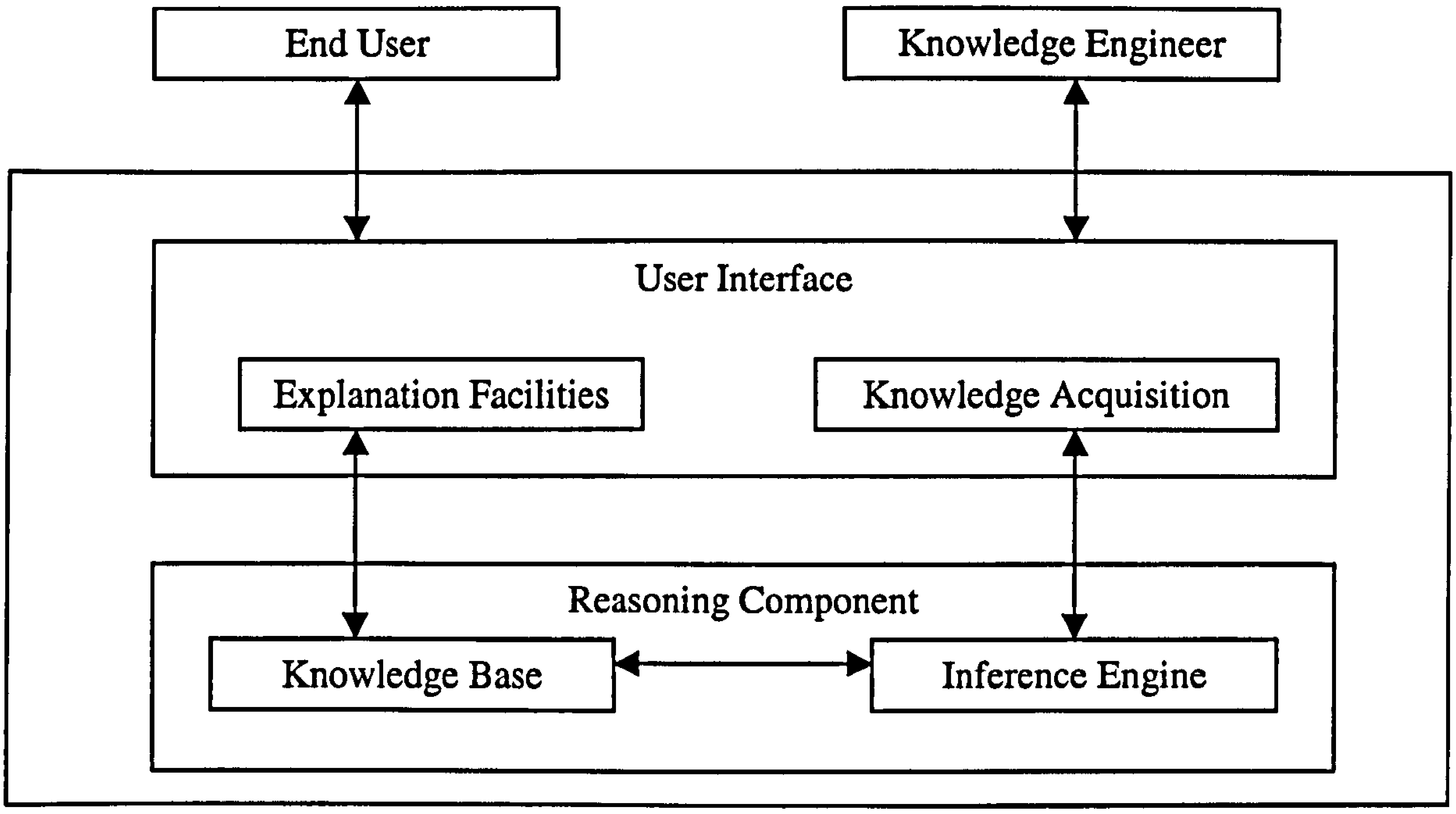
ii) intelligent decision modelling systems that help users build, apply and manage libraries of models; and

iii) decision analytic expert systems that integrate theoretically rigorous methods of certainty into the knowledge bases.

In summary, the KBMS consists of three intelligent components (Baek, *et al*, 1997). These are the: user agent; knowledge manager; and knowledge agent. Figure 3.7 is a commonly adopted logical illustration of a knowledge based management system (Zhang, 1999). Each component has a dialogue structure for users and other agents, a rule base and a database (Hinks *et al*, 2000; Hogg, 2000; Chua, 2001). A typical configuration of the dialogue structure and dialogue rule base are implemented using Javascript and its main rule base is implemented using Cold fusion, Doctus, etc and database such as Microsoft Access (Chen and Heath, 2001).

The user agent records all KM activities of users and dynamically organises agenda lists. A knowledge manager on the other hand determines the plan to perform and record changes that occurred in a knowledge repository. Finally, a knowledge agent provides intelligent access to storyboards, feedback messages and data libraries in a knowledge repository (Baek, *et al*, 1998; Guohua, 2000; Turban and Aronson, 2001).

Figure 3.7: Components of a KBMS (Zhang, 1999)



SUMMARY

Three-tier web based client-server architectures have been proven to provide a suitable hosting platform for intelligent systems (Sun *et al*, 1999; Liang and Garret, 2000, Nunnally, 2000; Chipman and Baron, 2001). The first and second tiers accommodate the user interface and the broker server respectively. The third tier hosts the 'intelligent' components, which include a: web-enabled RDBMS, MBMS and/or a KBMS.

The development of an intelligent web based off-highway plant information management system that is based on the three-tier architectures should improve off-highway plant information management. The RDBMS allows dynamic modelling of historical records (Anon, 1999a), an advantage over existing information management systems, which are modelled on fixed historical data (Turban and Aronson, 2001).

Also, the MBMS contains routine and special quantitative models that provide the analysis capabilities of the intelligent system (Zhang, 1999). This capability facilitates the building up of model blocks that predict plant breakdown, model faults and other plant parameters based on the dynamic plant history database. Finally, a KBMS could further provide additional intelligent system functionality when interfaced with the RDBMS and MBMS (Turban and Aronson, 2001; Timar, 1999).

CHAPTER FOUR: Pilot Studies and System Development Methodology

INTRODUCTION

The establishment of a robust research methodology was the primary focus of this chapter. The strategy was based on a consolidation of the literature review (chapters two and three) and the completion of a pilot study (details of which are also discussed in this chapter). Three vital aspects of this research are thus presented. First, a review of the generic approach for this research was discussed. Second, the pilot study objective, methodology and outcome were systematically presented and third, the overall system development methodology was established.

The formulation of the generic approach used for this research represented an 'offshoot' of an extensive review of established research methods (Rudestam and Newton, 1992; Brown *et al*, 1995). Salient components recommended for a comprehensive research methodology were investigated. These components were then adopted in line with the objectives of this work (Stuttard, 1994; Greenfield, 1996; Aouad and Sun, 1999). Two broad components were defined for the research methodology. These include: (i) the literature review and (ii) the theory building, theory testing and reflection. The literature review has been presented in the chapters two and three, while this chapter presents the outline methodology for the theory building, theory testing and reflection component. Seven additional sub-components (stages) were also defined in order to properly address the requirements of the theory building, theory testing and reflection component. The overall system development methodology was formulated based on these seven stages.

The first stage was a pilot study, which entailed the: establishment of data requirements, selection of and contacts with target respondents; follow-up interviews; evaluation of interview data and establishment of practitioner needs (Oppenheim, 1992; Cryer, 1996). Details of the approach to these pilot study activities were discussed, while the results were also presented within two broad group classifications. The first group described results collated as plant information management procedures, while the second group described the practitioner requirements as deduced from the survey. This information was collated and utilised as a basis for establishing the remaining six stages of the overall systems development.

The remaining six stages were defined as: (i) RDBMS design; (ii) selection of a modelling technique; (iii) exploratory analysis of historical data; (iv) the design of a MBMS; (v) component integration and web hosting; and (vi) system validation and testing. Detailed descriptions of each of the stages are hereby presented as follows starting with the overall generic approach.

GENERIC APPROACH

A two-part component was broadly defined as a generic approach to the development of a comprehensive research methodology. These were: (i) reviewing the field of investigation (literature review); (ii) theory building, theory testing and reflecting on and integrating the results (Stuttard, 1994; Greenfield, 1996; Aouad and Sun, 1999).

Specific considerations made in respect of each of these parts of the process are enumerated as follows.

Component One: Literature Review

The literature review studied current developments in off-highway plant information management research (Anon., 1999a; Anon., 1999b; Edwards, 1999; Nassar, 2001). As an initial procedure, the literature review broadly examined the types of existing off-highway plant information management systems and compared these with similar developments in some advanced industries (Oloke and Edwards, 2002). The methods used in conducting the literature review and the results obtained have been described in chapters two and three.

Component Two: Theory Building, Theory Testing and Reflection

The theory building process consisted of: inspecting and drawing inference from individual data cases (induction) and reaching conclusion about specific instances from general principles (deduction) (Weiss and Indurkhya, 1998). The 'deduction' procedure was based on the general theories of developing intelligent database systems, while the 'induction' was based on current practices in the utilisation of off-highway plant IT. Results from these two processes enabled the consolidation of the overall system development strategy (Kumar, 1999). Within chapter three, the deduction part was carried out and a framework for the theoretical development of the new system was conceptualised. The induction procedure (presented as part of this chapter), however, enabled a consolidation of this theoretical framework. This was via a pilot study in which the application of existing off-highway plant IT techniques were investigated. This investigation led to the identification of key issues that could enhance current techniques (Naoum, 1998). Methodological details of this pilot study are subsequently discussed.

Based on the establishment of a conceptual theoretical framework for the research, a system development procedure was evolved for INTELLIPLANT.

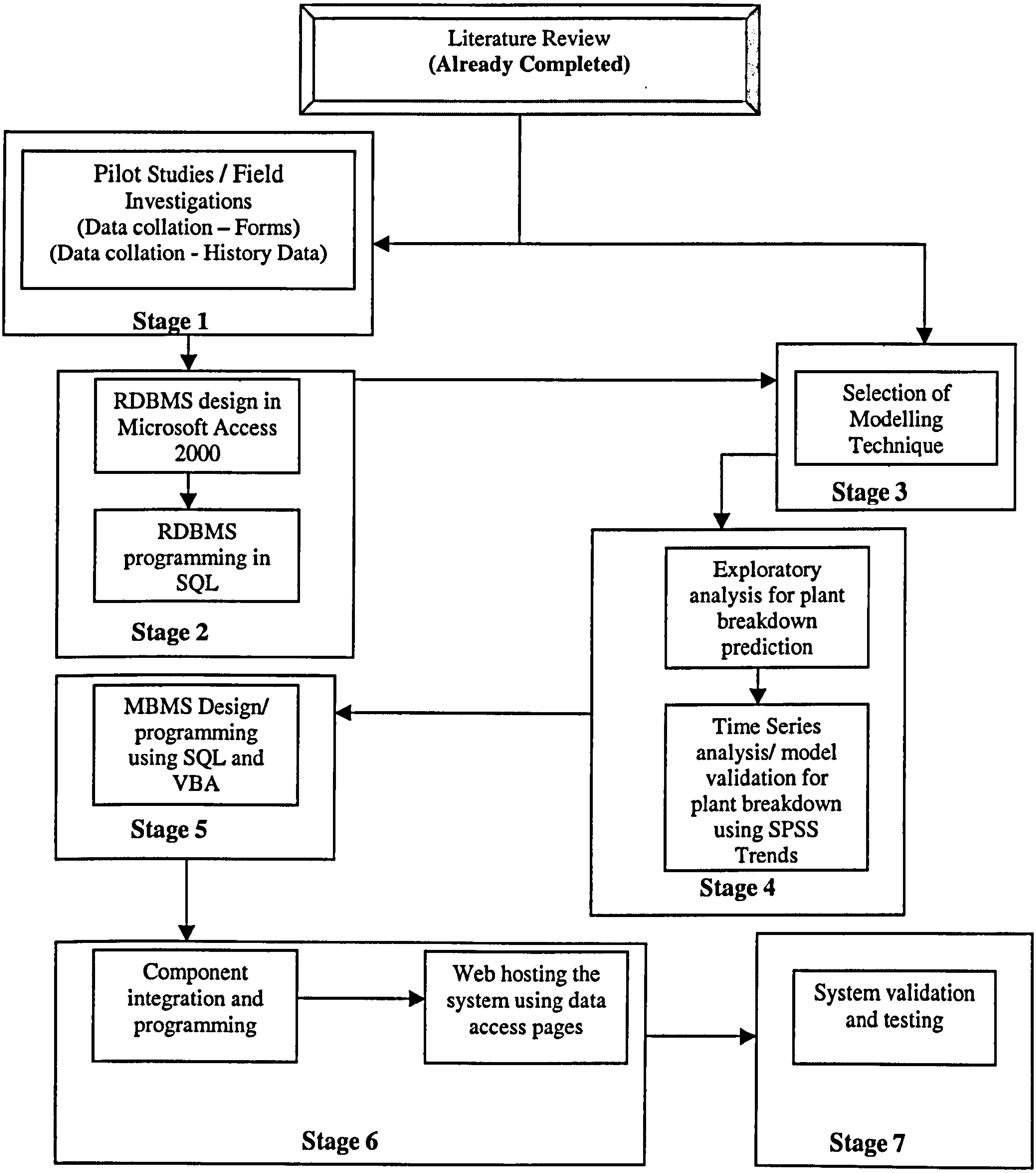
The theoretical framework developed for INTELLIPLANT was then tested through a performance assessment on the functionalities of INTELLIPLANT. The objective was to weigh the outputs INTELLIPLANT against expectations (Aouad and Sun, 1999; Greenfield, 1996). Subsequently, a reflection and integration procedure was conducted during which the major research contributions of the development to the field of practice were assessed and expressed (Jankowitz, 1991; Rogers, 1995). Recommendations for further research were also made to engender a progressive development of the research outcomes.

The comprehensive account overall system development (including the pilot study methodology and results) are hereby presented as follows.

OVERALL SYSTEM DEVELOPMENT METHODOLOGY

An overview of the system development methodology for INTELLIPLANT is presented in Figure 4.1. The flowchart shows the step-by-step procedure adopted in the system's development and particularly the logical sequence in which the distinct stages were carried out.

Figure 4.1: Flowchart of System Development Overview



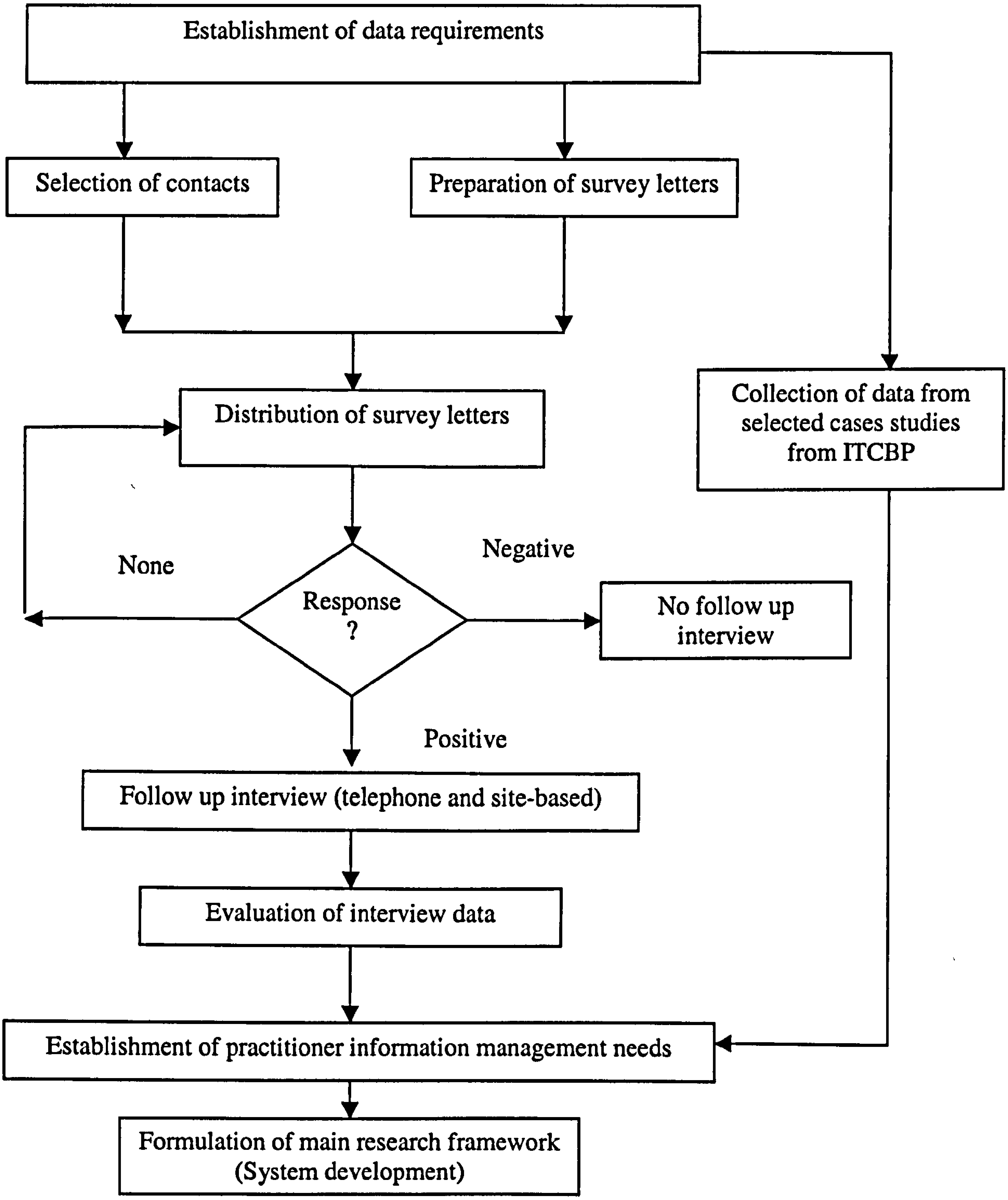
STAGE 1: PILOT STUDY

The pilot study was conducted as a means of ensuring a qualitative enhancement to existing off-highway plant IT tools. In achieving this, the study provided a means of understanding the practitioners' perceptions of existing systems and their expectations for new developments (Aouad and Sun, 1999). In addition, plant history data capture formats and actual history data were also collected as part of the pilot study. These data provided the quantitative databank on which suitable analytical procedures were conducted in order to model the desired parameters (Stuttard, 1994; Holt, 1998).

The pilot study benefited from the generous inputs of a wide range of industrial collaborators in the UK. These include; Lafarge – one of Europe's largest aggregate production companies, the UK Ministry of Defence, the National Association of Demolition Contractors, the Scottish Plant Owners Association and the Contractors Mechanical Plant Engineers (some of the correspondence received from these organisations are included in Appendix I). Many other plant manufacturers and plant hire companies also contributed immensely to the research during the site visits and phone interviews made. The invaluable inputs from these organisations allowed the collection of practitioner views on existing plant information management techniques and the inherent problems associated with their application.

An outline methodology of the pilot study is illustrated in Figure 4.2. For the pilot study, 60 top UK plant hire companies and contractors were selected using random number tables (Ruddock, 1995; Holt, 1998). The population was sourced from the "Where Hire?" plant directory and also the professional membership lists. To elicit opinion and provide relevant feedback, the pilot survey used a semi-structured questionnaire and a cover letter that explained the nature and purpose of the questionnaire. An iterative procedure was then applied prior to follow up interviews;

Figure 4.2: Flowchart of Pilot Study Methodology



that is, telephone interviews and site visits prior to formal meetings. Information collected from selected case studies of the Construction Federation's Information Technology Construction Best Practice (ITCBP) also enriched the survey findings (Anon., 2000). Essentially, the survey served to excoriate information on: current plant history data capture mechanisms and existing plant information management systems utilised within industry. This procedure ensured that data collection was optimised. As shown in Figure 4.2, once feedback from the letter was positive, a follow-up interview was scheduled. In the event that there was no response, the particular organisation was contacted again; and further correspondence with the particular organisation depended on the response. Data collected from the interviews were then evaluated to: establish practitioner information management needs; and aid the formulation of a research framework. An in-depth description of each of the processes is now discussed.

SITE INTERVIEWS AND CORRESPONDENTS

Site interviews conducted as part of the pilot study yielded a two-fold benefit. First, they publicised the research in order to engender wider participation and second, they served to channel 'much-desired' input and collaboration from industry. The selected interviewees included site managers, site planners and site engineers who have professional plant management experience (as exhibited by membership to one of various professional associations e.g. CMPE). The high response result (at 51 percent) and the enthusiasm expressed by practitioners provided demonstrable evidence of the need (and thus potential impact) for the work in industry (Oloke *et al*, 2001).

A listing of the organisations contacted is given in Appendix II. The listing shows the coverage of the sampling in terms of both geographical location and plant management functional category. The participating organisations were located throughout the UK and represented contracting organisations, plant manufacturers and plant hire companies. This sampling technique meant that the UK plant practitioner population was adequately represented (Greenfield, 1996; Weiss and Indurkhya, 1998).

FEEDBACK CATEGORISATION

Feedback received from this pilot study was classified into two broad groups in order to aid clarity. The first group, contained results obtained from requests for plant information management forms and procedures. The review concentrated on extracting information on the paper-based formats. Since only a few of the organisations contacted had electronic systems and these tended to be very rudimentary.

The second group relates to data collected from the pilot study surveys to establish practitioner/industry requirements for improving plant information management. These statistics were obtained from plant practitioners and manufacturers who own, lease and /or maintain plant items. A more exact and comprehensive description of information collected under both categories is now given.

GROUP ONE: PLANT INFORMATION MANAGEMENT AND PROCEDURES

Results under this first group were further sub-divided into three different sub-groups as follows: data input forms; plant manufacturer's data; and plant history data.

Data Input Forms (Paper Formats)

Data input forms are the most common data recording formats available in the industry (Day and Benjamin, 1991; Edwards *et al*, 1998). Various forms are used to capture plant history data that relate to the different aspects of plant history information management (Edwards, 1999; Nassar, 2001). This aspect of the pilot study sought to critically examine these forms in order to extract salient data inputs and any relationship existing between these forms.

From an operational point of view, each item could be engaged on one or more project sites at any given time. The plant holding company, therefore, kept an inventory file showing the plant details such as machine code, description, model type, quantity in fleet, current status, usage summary and transfer details. In addition to these, records were also kept on stock items, stock adjustments, goods received and goods issued in respect of each plant item. To ensure effective maintenance management, the company maintained a comprehensive record of each plant item's specification. Information kept includes calibration records, pressure checks and engine and transmission evaluations. Samples of the forms collected as part of this pilot study are given in Appendix III.

In line with the literature review findings, it was also discovered that practitioners utilise a wide range of paper-based forms for the documentation of plant data. Documentation, in this case, is a complex terminology that includes storage, retrieval and transmission of data (Rowley and Butcher, 1998; Nunnally, 2000). These paper forms capture data relating to inventories, specifications, maintenance, health and safety checks, etc (Wetzel, 1998; Edwards, *et al* 1998). Such forms were thus collated in order to assess similarities in the plant history data capture formats. Generally, this information facilitated the design of the data entry components of the intelligent system.

In addition, a general description of the contents and use of the common forms had also been investigated by Edwards *et al* (1998). The results from this pilot study and previous research therefore, enabled the following descriptions of the forms:

- Plant Inventory – a comprehensive list of all facilities, which need maintenance. It also serves as a useful reference for identifying where capital is tied up in a business. Most companies kept an inventory because it provides a readily available source of information on plant status, e.g. additions, depletions, replacements and location.
- Maintenance Programme – which provides specifications for the individual plant items relating to the methodology and frequency of maintenance required.
- Machine Maintenance Report – these are essentially a factual recording by engineers in-charge-of maintenance conducted on plant items. They also include a subjective statement of general maintenance condition.

- Machine Cost Estimation – this is used to plan for future cost expenditure and control current cost expenditure.
- Maintenance Planning Charts – essentially provide general details on planned plant inspection and maintenance activities.
- History File Forms – this supplies a readily available quick reference guide from whom senior management can analyse the inherent success or failure of their maintenance policy.

A variety of other forms are available under the major headings mentioned above.

From the pilot study, the extent and complexity of documentation kept by plant owners is a function of many parameters. These include, types and sizes of equipment in the fleet, type of maintenance management programme being adopted, etc. A major finding was that these paper formats entailed a rigorous procedure of recording relevant information on a periodic basis. As already observed, this leads to the development of bulky documentation over a long period of time. In addition, these formats do not allow a free flow of plant history across plant sites.

Plant Manufacturer Data (Specifications)

The second category of data collected was plant manufacturer machine specification data that described the potential performance of such machines. Specification data is important to the practitioner since it enables the correct maintenance system to be developed and defines the use and functionality of the machine. Such data enabled the compilation of the general format of plant specification capture within the database.

A total of 55 manufacturers specifications were collated. Most of the data were excerpts from the companies' plant specification manuals. These were supplied by kind consideration of the manufacturers for the purposes of this study. Summaries of the data collated are given in Table 4.1. The table shows the data collected as grouped into 27 equipment model types. These data showed that plant items could generally be identified by specifications relating to physical and operational data.

Plant History Data

Plant history data (under the pilot study) was collected and collated from actual plant history records held by participating contractors. In total, six contractors assisted in the exercise. Data collected facilitated the design and testing of an electronic data capture mechanism - a fundamental component requirement of an intelligent information management system (Bertino *et al*, 2001).

Historical data collected ranged from plant utilisation and breakdown records to plant maintenance records from the different sources. It is notable that the records that were available on a comprehensive scale were from plant items manufactured by companies such as Volvo, Samsung and Caterpillar. This is because of the forms supplied by the manufacturers. These data aided the design of the key components and the deterministic analysis for plant breakdown prediction as a precursor to the development of the system's intelligent components (Carter, 2000; Howe, 2001). More comprehensive details of such records are given later in the thesis where they were utilised for model development. However, for brevity, data contained the actual plant types and models collated, the number of observations and details of the participating firms.

TEXT BOUND INTO

THE SPINE

Table 4.1 (Cont'd): Details of Data Types Collected from Plant Manufacturers

S/No.	Manufacturer	Equipment Type	Typical Models	Specifications (Components and Operational)
12	Case	Wheel Loader	621C, 621CXT, 621CXR, 721C, 721CXT, 721CXR, 821C, 821CXR, 921C, 921CXR	Dimensions, Bucket Capacity, Lifting Capacity, Engine, Electrical System, Hydraulic System, Slewing System, Service Refill Capacities, Weight and Axle Load
13	Manitou	Masted Forklift Truck	MSI20D, MSI25D, MSI30D, MSI20G, MSI25G, MSI 40, MSI50, MC30, MC40, MC50, MC60T, MC70T, MC20HP, RM20HP, M26.2, M30.2, M26.4, M30.4, M40.4, M50.4, MA460, MA470	Dimensions, Weight, Tyres, Engine, Electrical System, Transmission, Axles, Hydraulic System, Steering, Cab, Capacities
14	Euclid	Pay Loader	R32C, R40C, R65C, R90C, R130B, R150, R170, R190, R260	Dimensions, Load Capacity, Engine, Electrical System, Weights, Hydraulic System, Transmission, Tyres and Braking system, Final Drives, Service Fill Capacities
15	Manitou	Maniscopic Range	TMT315, TMT320, TMT320FL, TMT 325, BT420, BT425, BT220, BT225, MT 732, MT932, MLT524, MT527, MLT629, MLT633, MLT730, MLA627, MVT 665, MVT675, MT835, MT845, MT940L, MT1233S, MT1240L, MT1330SL, MT 1337SL, MT 1637SL, MT1637SL, MRT1432/1542, MRT 1650/1850	Dimensions, Weight, Tyres, Engine, Electrical System, Transmission, Axles, Hydraulic System, Steering, Cab, Capacities
16	Liebherr	Wheel Excavator	A310, A312, A316, A914Lit, A954Lit, A900BLit, A904Lit, A924Lit, A932Lit	Dimensions, Digging Data, Engine, Electrical System, Hydraulic System, Transmission, Swing, Axles, Brakes system, Steering System, Tyres, Service Fill Capacities
17	Liebherr	Tracked Excavator	R310B, R312, R900BLit, R900Lit, R914Lit, R924Lit, R934Lit, R944Lit, R954BLit, R964BLit, R974BLit, R984CLit, R992Lit, R994Lit, R995Lit, R994Lit	Dimensions, Digging Data, Engine, Electrical System, Hydraulic System, Transmission, Swing, Controls, Undercarriage, Service Fill Capacities
18	Liebherr	Wheel /Tracked Loader	L507, L509, L522, L531, L564/ LR621, LR632	Dimensions, Digging Ranges, Lifting Capacity, Engine, Electrical System, Hydraulic System, Slewing System, Care Cab, Undercarriage, Service Refill Capacities, Weight and Axle Load/Tracks, Noise Levels
19	Liebherr	Tracked Dozer	PR722Lit, PR752	Dimensions, Engine, Electrical System, Hydraulic System, Transmission, Steering and Braking system, Final Drives, Track, Service Fill Capacities, Ripper
20	Liebherr	Crawler Cranes	HS833Lit, HS843Lit, HS853Lit, HS873Lit, HS883Lit	Dimensions, Engine, Electrical System, Hydraulic System, Transmission, Swing, Controls, Capacities

Table 4.1 (Cont'd): Details of Data Types Collected from Plant Manufacturers

S/No.	Manufacturer	Equipment Type	Typical Models	Specifications (Components and Operational)
21	Liebherr	Crawler Tractors and Loaders	PR712B, PR722B, PR732B, PR742B, PR751, PR752, RL22B, RL42B, SR712BMLit, LR611, LR622, LR632, LR641	Dimensions, Bucket Performance Data, Engine, Electrical System, Torque Converter, Transmission, Axles, Brakes, Tracks, Hydraulic System, Steering, Cab, Capacities
22	Liebherr	Wheel Loader	L504AP, L506, L507, L508, L509, L512, L512, L522, L534C, L538, L544, L564, L574, L580	Dimensions, Operating Data, Engine, Electrical System, Drive train, Service Fill Capacities, Braking System, Hydraulic System, Steering, Bucket Performance, Linkage
23	Hyundai	Wheel Loader	HL750, HL750TM, HL770, HL730-3, HL730TM-3, HL780-3	Dimensions, Operating Data, Engine, Electrical System, Drive train, Service Fill Capacities, Braking System, Hydraulic System, Steering, Bucket Performance, Linkage
24	Hyundai	Hydraulic Excavator (Tracked)	R210-3, R210LC-3, R250LC-3, R250NCL-3, R290-3, R290LC-3, R290NLC-3, R360-3, R360LC-3	Dimensions, Digging Data, Engine, Electrical System, Hydraulic System, Transmission, Swing, Controls, Undercarriage, Service Fill Capacities
25	Hyundai	Mini Excavator (Wheel)	R55W-3	Dimensions, Lift Capacity, Weight, Engine, Electrical System, Hydraulic System, Performance, Undercarriage, Service Fill Capacities
26	Hyundai	Wheel Excavator	R95W-3, R130W-3, R200W-3	Dimensions, Digging Data, Engine, Electrical System, Hydraulic System, Transmission, Swing, Axles, Brakes system, Steering System, Tyres, Service Fill Capacities
27	Merlo	Panoramic Lift and Handler	P27.9EVX, P28.7EVS, P28.9EVS, P30.7EVX, P32.17EVS, P35.7EVX, P35.9EVS, P35.11EVS, P35.13EVS, P40.8EVS, P40.16EVS, Roto 10.18EVS-40.21EVS, P60.10EV	Dimensions, Weights, Performances, Engine, Operating Times, Travel Speeds, Hydraulic System, Boom, Carriage, Pallet Forks, Frame Levelling, Steering, Service Hydraulics, Electrics, Capacities
28	Komatsu	Crawler Tractors and Loaders	D21A-7, D31E-20, D32E-1, D37E-5, D38E-1, D39E-1, D39E-1, D37E-1, D39E-1, D41E-6, D50A-17, D53A-17, D58-17, D58E-17, D58E-1, D60E-8E, D65E (Range), D70LE-8, D85E (Range), D155A (Range), D355A-3, D475A (Range), D575A (Range)	Dimensions, Bucket Performance Data, Engine, Electrical System, Torque Converter, Transmission, Axles, Brakes, Tracks, Hydraulic System, Steering, Cab, Undercarriage, Capacities
29	Komatsu	Wheel Loader	L504AP, L506, L507, L508, L509, L512, L512, L522, L534C, L538, L544, L564, L574, L580	Dimensions, Operating Data, Engine, Electrical System, Drive train, Service Fill Capacities, Braking System, Hydraulic System, Steering, Bucket Performance, Linkage
23	Hyundai	Wheel Loader	HL750, HL750TM, HL770, HL730-3, HL730TM-3, HL780-3	Dimensions, Operating Data, Engine, Electrical System, Drive train, Service Fill Capacities, Braking System, Hydraulic System, Steering, Bucket Performance, Linkage
24	Hyundai	Hydraulic Excavator (Tracked)	R210-3, R210LC-3, R250LC-3, R250NCL-3, R290-3, R290LC-3, R290NLC-3, R360-3, R360LC-3	Dimensions, Digging Data, Engine, Electrical System, Hydraulic System, Transmission, Swing, Controls, Undercarriage, Service Fill Capacities

Table 4.1: Details of Data Types Collected from Plant Manufacturers

S/No.	Manufacturer	Equipment Type	Typical Models	Specifications (Components and Operational)
25	Hyundai	Mini Excavator (Wheel)	R55W-3	Dimensions, Lift Capacity, Weight, Engine, Electrical System, Hydraulic System, Performance, Undercarriage, Service Fill Capacities
26	Hyundai	Wheel Excavator	R95W-3, R130W-3, R200W-3	Dimensions, Digging Data, Engine, Electrical System, Hydraulic System, Transmission, Swing, Axles, Brakes system, Steering System, Tyres, Service Fill Capacities
27	Merlo	Panoramic Lift and Handler	P27.9EVX, P28.7EVS, P28.9EVS, P30.7EVX, P32.17EVS, P35.7EVX, P35.9EVS, P35.11EVS, P35.13EVS, P40.8EVS, P40.16EVS, Roto 10.18EVS-40.21EVS, P60.10EV	Dimensions, Weights, Performances, Engine, Operating Times, Travel Speeds, Hydraulic System, Boom, Carriage, Pallet Forks, Frame Levelling, Steering, Service Hydraulics, Electrics, Capacities

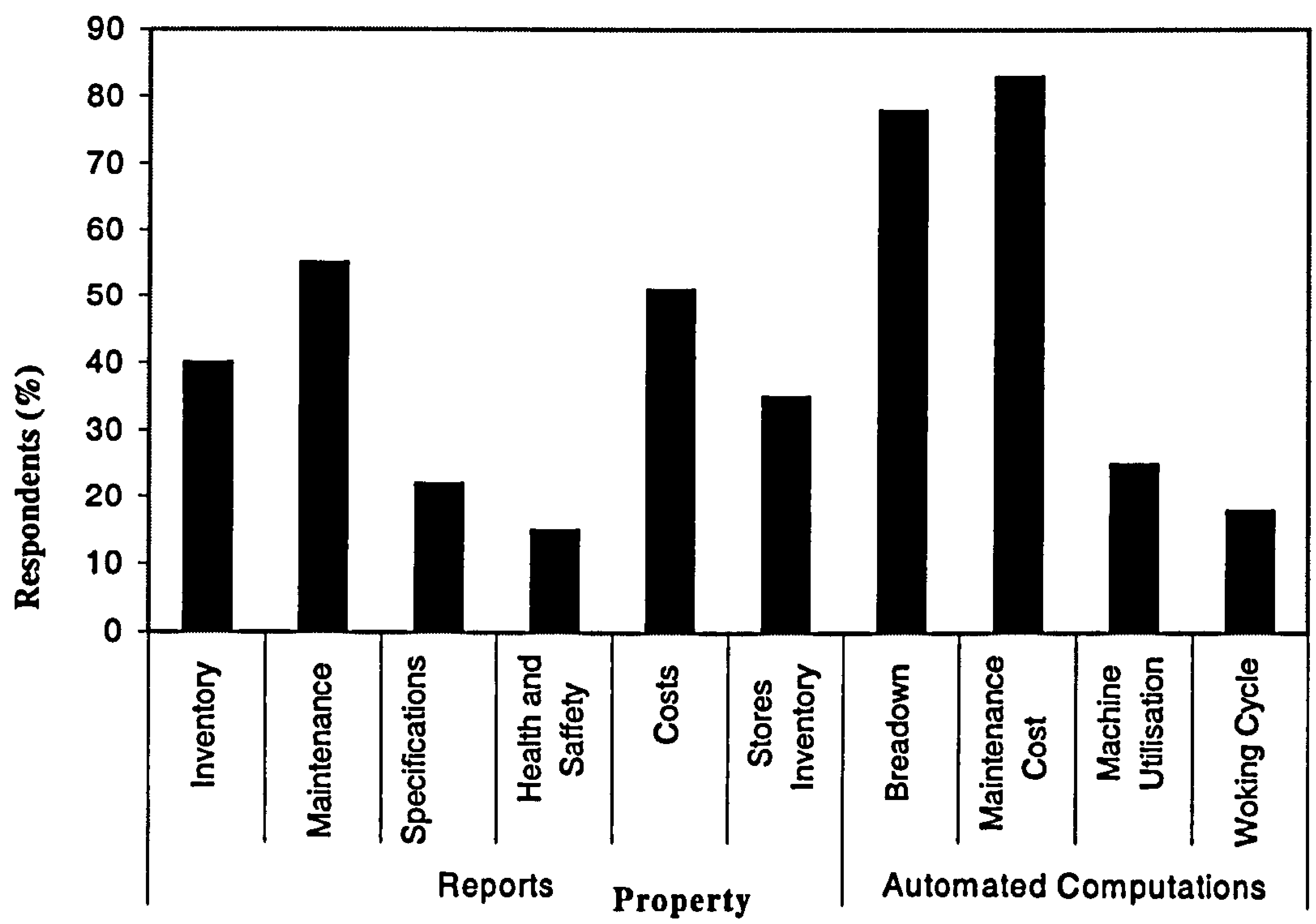
GROUP TWO: PRACTITIONER/INDUSTRY REQUIREMENTS

The requirements for improved plant information management, as perceived by practitioners, constituted the second broad group. In doing this, the survey requested respondents to supply information relating to their plant information management procedures, technologies and envisaged requirements. Emphasis in this group was placed on the interview results, which enumerated the manner in which the forms and data in the first group were being utilised. The interview results also highlighted the envisaged practitioner requirements for improving plant information management.

Interestingly, a high proportion (61%) of respondents failed to maintain any meaningful 'formal' plant history data capture mechanisms. Conversely, 25% kept an informal paper-based documentation of plant history records such as inventory details and maintenance records.

The remaining 14% had some form of electronic information management system (either PC or network based) for plant documentation. Practitioners proffered various reasons as to why only a minor proportion of plant users adopt formal paper or electronic plant information management systems. These range from the limitations of paper documentation (already highlighted in chapter two) to the prohibitive cost of purchasing and operating software and associated hardware requirements. In addition, the investment in personnel to administer such systems was perceived to be substantial and beyond company's resources. Most respondents also stated that existing static electronic database systems do not provide a dynamic decision support capability. Hence, whether the system is paper or electronic based, users are confronted with an inability to interpret reports generated by such systems; unless of course, lengthy manual mathematical manipulation of the data is employed. Finally, the majority (over 75 per cent) of practitioners indicated that they would appreciate a system, which could automate the prediction of plant breakdown and maintenance costs based on each plant item's history file (Oloke and Edwards, 2001). Results of the field survey are presented in Figure 4.3. This figure shows that practitioners actively sought a system that was capable of producing reports of inventories, maintenance records, specifications and plant historical costs. It was also inferred that such a system should permit ease of data update due to the dynamic nature of plant records.

Figure 4.3: Field Survey Results: The Need for Automated IT



APPLICATION OF THE PILOT STUDY RESULTS

The existing forms and historical data collected from the pilot studies were collated as a means of designing input forms for the database and modelling plant breakdown events for the model base respectively. The major purpose was to ensure that the forms collated represent the most frequently captured plant history data. This procedure was to enhance the human-computer interaction of INTELLIPLANT. Actual plant history data relating to inventories, maintenance, breakdowns, utilisation, breakdown, fault logging, and standing time were also collected. These data were subsequently used for analysis for the development of plant breakdown prediction models.

STAGE 2: RDBMS DESIGN

This entailed the organisation of the collated forms into entities that were linked together via the design of an entity-relationship model. Each entity was normalised and the relationships between entities were established to ensure that referential integrity was enforced. During this stage the graphical user interface (GUI) for the forms and on-line database reports was also designed. Extensive SQL programming and the application of macros also facilitated the development of the RDBMS and the interface with the MBMS.

STAGE 3: SELECTION OF APPROPRIATE MODELLING TECHNIQUE

Various methods of modelling techniques were evaluated after a preliminary analysis of the data. Modelling techniques such as neural networks, genetic algorithms, hybrids of neural networks and genetic algorithms, fuzzy logic and time series analysis were investigated. This evaluation led to the selection of the time series analysis approach. The time series approach was particularly selected because it is a technique that facilitates the prediction of dependent variables from historical records. In addition, the method identifies the nature of the trend of the sequence of observations and also predicts future values of the observed series.

STAGE 4: EXPLORATORY ANALYSIS OF PLANT HISTORY DATA

Collated plant history data relating to fault logging, plant utilisation and breakdown were subjected to an exploratory analysis using time series. This enabled the identification of the most suitable predictor technique and a selection of independent and dependent variables for plant breakdown prediction. Based on the selection of the time series approach, the predicted dependent variable (plant breakdown percentage) was assessed based on a rigorous trial of the combination of four independent variables. These are the lagged plant breakdown percentage time, the utilisation percentage time, the percentage of fault occurrence and the standing percentage time.

STAGE 5: MBMS DESIGN

The model base design entailed a detailed analysis of additional data. This detailed analysis was based on the selected time series method. The models were then organised into a model base and programmed for selection and intelligent application through indexing and SQL programming. The models developed and incorporated within the MBMS enable the prediction of plant breakdown percentage time for the following plant items: wheel loaders, backhoe-loaders, hydraulic excavators and off-highway haulers.

STAGE 6: COMPONENT INTEGRATION AND WEB HOSTING

During this stage the RDBMS and the MBMS were integrated using VBA to enable a synchronised functionality of the INTELLIPLANT system. The system was then web enabled using SQL server 2000. Web enabling INTELLIPLANT facilitated the database sharing functionality of the system. It permitted system access from various locations as may be required by the users.

STAGE 7: SYSTEM VALIDATION AND TESTING

System validation was based upon practitioner evaluation of INTELLIPLANT. Feedback was monitored in terms of: the ease of accessibility to the system, the ease of navigation within the system, security concerns and the accuracy of plant breakdown prediction from plant item to plant item.

SUMMARY

The adopted generic approach to this research methodology led to a two-component research structure. The first component was a literature review and the second component refers to a process of theory formulation, testing and integration. Details of the literature review had been presented in chapters two and three. However, in order to properly address the requirements of the theory formulation, testing and integration component, seven (sub-component) stages emerged for the development of the system. These were the: pilot study; RDBMS design; data synthesis and selection of modelling technique; exploratory analysis of plant history data; MBMS design, component integration and web hosting; and system validation and testing.

The pilot study was the first stage and was undertaken with the aim of identifying the shortcomings inherent within existing systems and also determining the needs of plant managers. This had led to the development of a system that is an improvement upon those currently utilised. The wide range of UK industrial collaborators that participated in the study served to provide the platform on which the study was based.

Data collated under the pilot study were classified two broad categories. The first category grouped data collated on plant information management forms and history. These data were further subdivided into three distinct sub-groups of: data input forms; plant manufacturer's data; and plant history data. The second category of data collated was for data relating to practitioner/industry requirements. These categorisations enabled data capture within the applicable contexts of the proposed system development.

The limitations of paper documentation and the cost of purchasing and operating software and associated hardware requirements are major factors affecting the efficient utilisation of current plant information management systems. The pilot study also revealed that practitioners sought a system, which could automate the prediction of plant breakdown events based on each plant item's history file. Such a system should also be capable of producing reports of inventories, maintenance records, specifications and plant historical costs. These findings therefore, formed significant inputs to the design of the intelligent plant information management system.

Brief descriptions of the six succeeding stages (i.e. RDBMS design; data synthesis and selection of modelling technique; exploratory analysis of plant history data;

MBMS design, component integration and web hosting; and system validation and testing) were also presented. Details of these are given in the successive chapters commencing with the RDBMS design in chapter 5.

CHAPTER FIVE: INTELLIPLANT - Design of the Relational Database Management System (RDBMS)

INTRODUCTION

The RDBMS platform constitutes the main operating platform for INTELLIPLANT's plant history data capture and report generation capabilities. INTELLIPLANT's RDBMS was designed on established relational modelling techniques. Relational modelling entails the establishment and synchronisation of several Tables (entities) in which various data may be stored. The main objective is to prevent duplication of entries and to ensure update of related records with minimal effort. The development of an efficient relational model for an organisation therefore requires a critical examination of the record keeping techniques of that organisation.

For plant information management, various plant history data must be monitored. Monitoring must coincide with the implementation of stringent management practices such as inventory control, maintenance, health and safety practices and so on. Efficient information management therefore, guarantees individual plant and overall fleet efficiency. Information kept in order to achieve fleet efficiency includes: daily breakdown summaries within the entire fleet, daily time sheets, plant maintenance status, servicing and maintenance records and schedules, site fitters daily record and weekly worksheets. Similarly, costs incurred for parts and consumables acquisition, operation and maintenance of the plant must also be monitored. This is achieved by manipulation of historical costs to obtain cumulative costs/expenditure Figures and other relevant statistics such as for parts purchase, machine jobs, unit jobs and overall weekly expenditure.

Traditional manual techniques for the computations of cumulative parameters involve the application of lengthy mathematical manipulations. However, the fundamental objective of INTELLIPLANT is to utilise historical records to make forecasts of plant breakdown time (Oloke and Edwards, 2001). Whilst the INTELLIPLANT system focuses on breakdown, future work could expand on the technique to cover other aspects of pant management such as maintenance, finance, etc. Therefore, apart from the RDBMS's data input and report generation capabilities, the system also provides a logical means of interface with the MBMS. This is because the auto-selection of plant breakdown time prediction models within the MBMS provides the intelligent capabilities of INTELLIPLANT.

Within this chapter, an overview of the INTELLIPLANT RDBMS development cycle is given. This commenced with a detailed description of the problem specification and the conceptualisation of a database schematics. The final schematic was then built on a robust entity-relationship modelling procedure, creation of desirable attribute lists and the normalisation of attribute lists. To illustrate the inherent simplicity, data capture and on-line/ real time report generation capabilities of INTELLIPLANT, a number of screen dumps from the RDBMS are included.

DATABASE DESIGN: PRAGMATIC CONSIDERATIONS

The prerequisite requirements for designing a RDBMS for are many. Amongst other things, the system should be user friendly and permit ease of data update due to the dynamic nature of plant history (Hendrickson, 2000). Therefore, an in-depth understanding of user-requirements and capabilities and detailed knowledge of database design.

To ensure user friendliness of INTELLIPLANT, various unique considerations must be embraced. The first consideration was the range and number of users that could access/utilise the system. This includes all the plant operators, maintenance engineers, plant managers and other plant information management operatives within an organisation. In essence, the GUI should be easily understandable and navigable. This enabled the various cadres of technical and managerial staff responsible for data input and performance reporting to utilise the system with minimal training and technical support. This was one of the requirements that emanated from the pilot work.

Second, plant history records are highly dynamic and are usually a function of the extent of plant utilisation, operational environment and operator competence. Maintenance records, for instance, could consist of planned maintenance activities or predictive/proactive maintenance details or some combination of previously cited strategies. For the former, records are updated in a cyclical pattern, say weekly, monthly or bi-monthly depending on the maintenance programme being adopted. For the latter, records are updated in an ad-hoc manner and is dependent on the frequency of plant breakdown occurrence. The design of the RDBMS must therefore account this type of dynamic database management by incorporating suitable sorting and structuring functions.

A relational database structure was selected from the list of available options such as hierarchical and network database structures. This selection was due to its advantages over the other systems when evaluated in line with the technical objectives of INTELLIPLANT. Table 5.1 shows the comparative analysis conducted on the properties of each database structure.

Table 5.1: Relational, Hierarchical and Network Database Structures

		Database Structure		
S/No	**Property**	**Relational**	**Hierarchical**	**Network**
1	Entities	Tables	Records	Records
2	Attributes	Columns	Fields of Records	Fields of Records
3	Relationships	Foreign Keys	Hierarchical tree structure of records	Network of Linked lists
4	Access to/ manipulation of data	Relational Algebra implemented/standardised by SQL	Programmatic (COBOL, etc.)	Programmatic (COBOL, etc.)

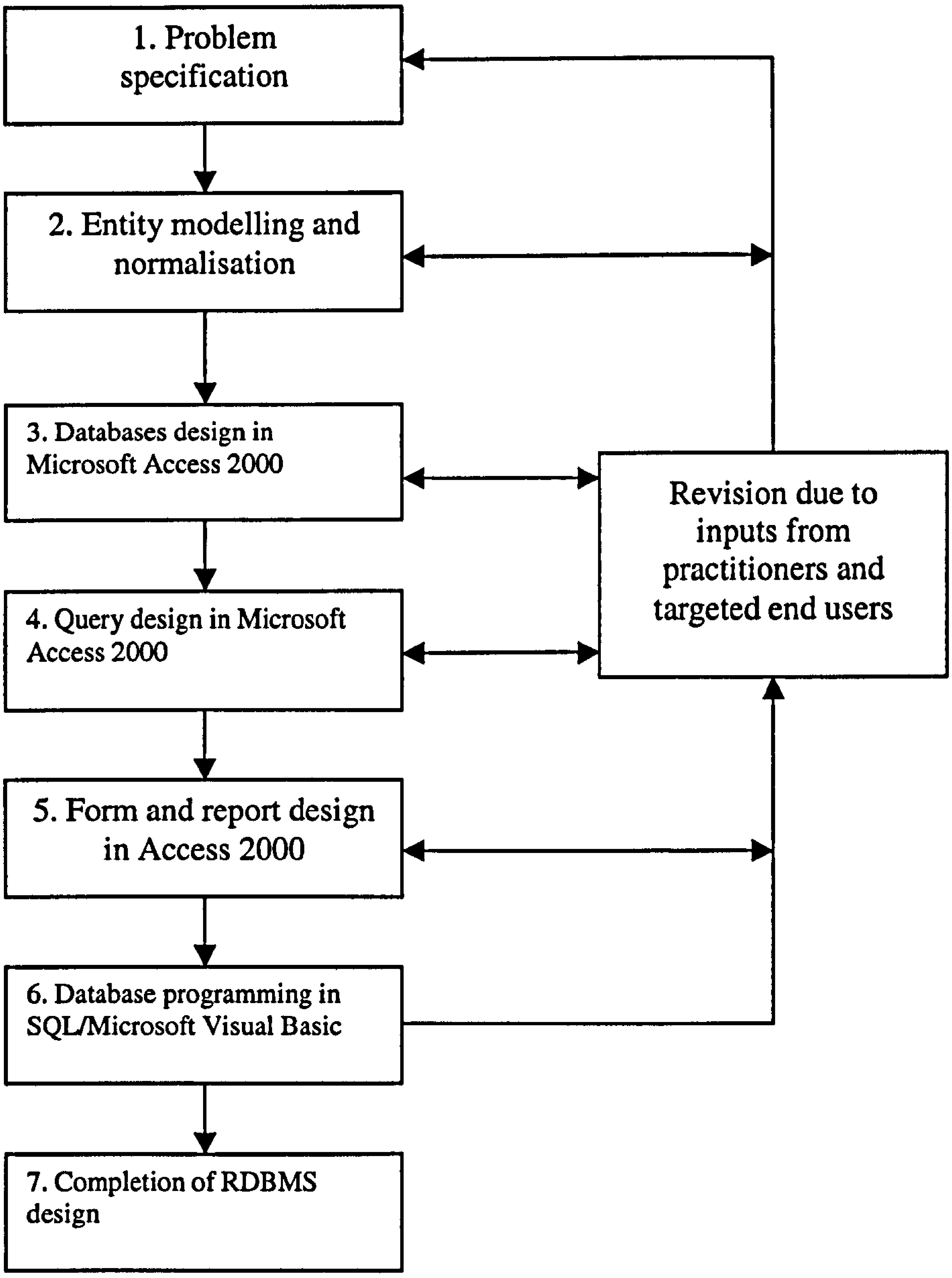
Advantages of the relational structure include; the simplicity of capturing plant history forms as Tables and columns; the use of foreign keys (i.e. attributes that help to define a relationship to an externally related table) to facilitate relationships between attributes of forms (Tables); and the simplified access to/manipulation of data using relational algebra/SQL as opposed to programmatic languages. Hence, the RDBMS was designed to ensure that relevant plant operations data were captured and managed most effectively. This design approach ensures that plant documentation collected, in respect of each activity (e.g. purchase, maintenance, etc.), is 'filed' in the appropriate table within the relational database structure. Also, a principal requirement of the RDBMS for INTELLIPLANT is that it is able to generate real time report sheets on-line. The selected design approach was therefore considered most appropriate as it also permits the development and integration of queries. These queries in turn enable the generation of up-to-date reports based on the plant history information contained on the database.

A diagrammatic representation of the procedure adopted for the design of the RDBMS is provided in Figure 5.1. The procedure commenced with the problem specification, which defined the RDBMS objective and the anticipated outputs. Based on this, the RDBMS was conceived as an entity model (i.e. a model in which relationships exist between the different Tables contained in the database). This model was subsequently normalised (by removing all unnecessary duplicate entries) to facilitate optimal performance of the database. All other aspects of database design, query and form design and database programming were then based on the normalised entity model. Details of each process of the development cycle are now explained.

PROBLEM SPECIFICATION

A set of objectives was drawn up for INTELLIPLANT's RDBMS based upon the pilot work conducted (Oloke and Edwards, 2001). Fundamentally, INTELLIPLANT's RDBMS is designed to significantly enhance plant record storage, retrieval and historical data reporting.

Figure 5.1: The development cycle for a typical off-highway plant RDBMS



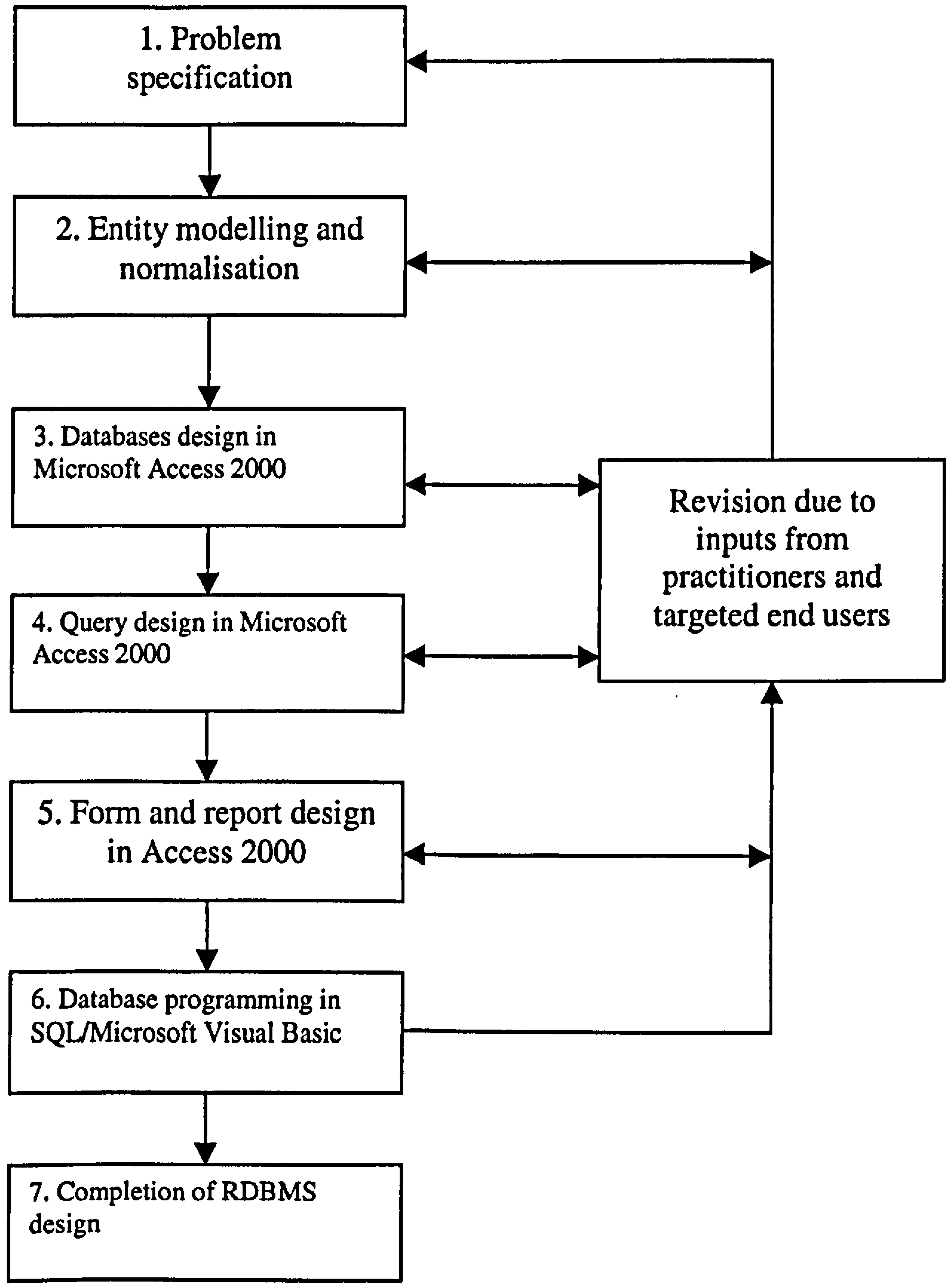
These objectives include the on-line and real time:

i) display of entry forms for the input of pertinent data relating to plant history records;

ii) reports outputs which detail stock items, plant inventory and plant status (including inter-site transfer);

iii) reports on plant technical specifications and compliance with standards such as health and safety;

Figure 5.1: The development cycle for a typical off-highway plant RDBMS



These objectives include the on-line and real time:

i) display of entry forms for the input of pertinent data relating to plant history records;

ii) reports outputs which detail stock items, plant inventory and plant status (including inter-site transfer);

iii) reports on plant technical specifications and compliance with standards such as health and safety;

iv) output of report on plant idle times;

v) output of reports on plant maintenance scheduling/planning;

vi) output of reports on individual plant maintenance activities (e.g. parts changed, serviced, Used Oil Analysis, etc); and

vii) output of all reports relating to plant purchase and maintenance costs.

THE DATABASE SCHEMA

The entity modelling technique was employed to produce an initial RDBMS design of and include the definition of entity types that will store data. The entity model was developed as a schematic model showing the relationship between the entity types. Sequel to this, attribute lists were drawn up after which a normalisation of the data sets was also carried out. The database schema was then formed from the documentation set consisting of the entity model and attribute lists results. Figure 5.2 illustrates the iterative steps used to produce the schema; this structured approach ensured the;

i) production of a database which can be understood by plant professionals;

ii) minimisation of duplication of data within the database;

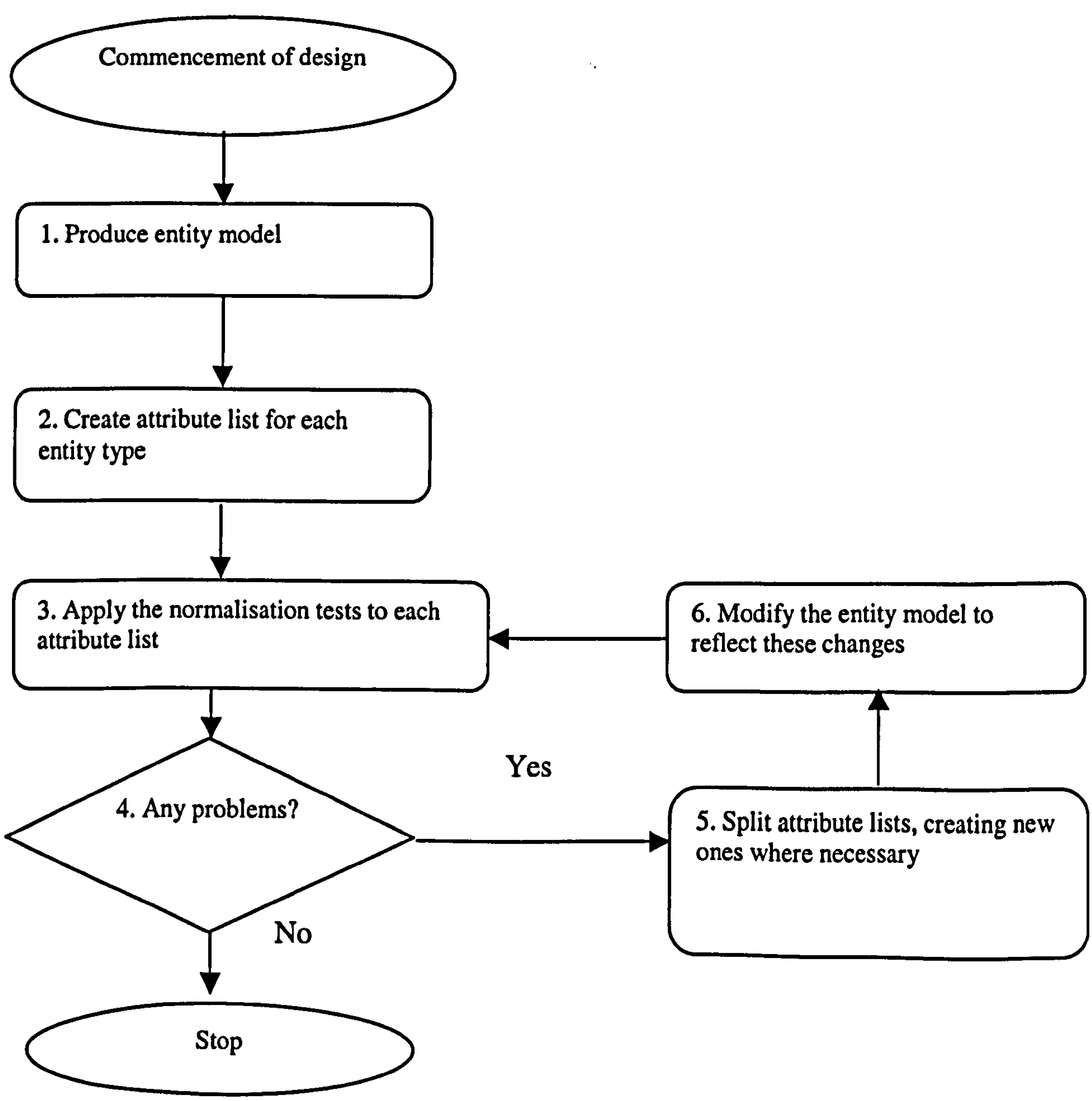
iii) production of a document, the entity model, which shows clearly the tables and relationships contained within the database; and

iv) production of a document that shows fields within Tables produced.

Entity Modelling

The entity model was conceived and designed as an inter-relationship between six entity types within the database and was based on literature reviews, field investigations and the pilot studies. Specifically, these six entity types are: plant inventory; stock inventory; specifications; maintenance; health and safety checks; and costs. The selected entity types represent the objects within which pertinent data relating to plant information management could be stored. In order to develop an entity-relationship (E-R) model, the lines of dependence between the entity types of the database (at any point in time) were evaluated. These relationships are as illustrated in Figures 5.3 to 5.7.

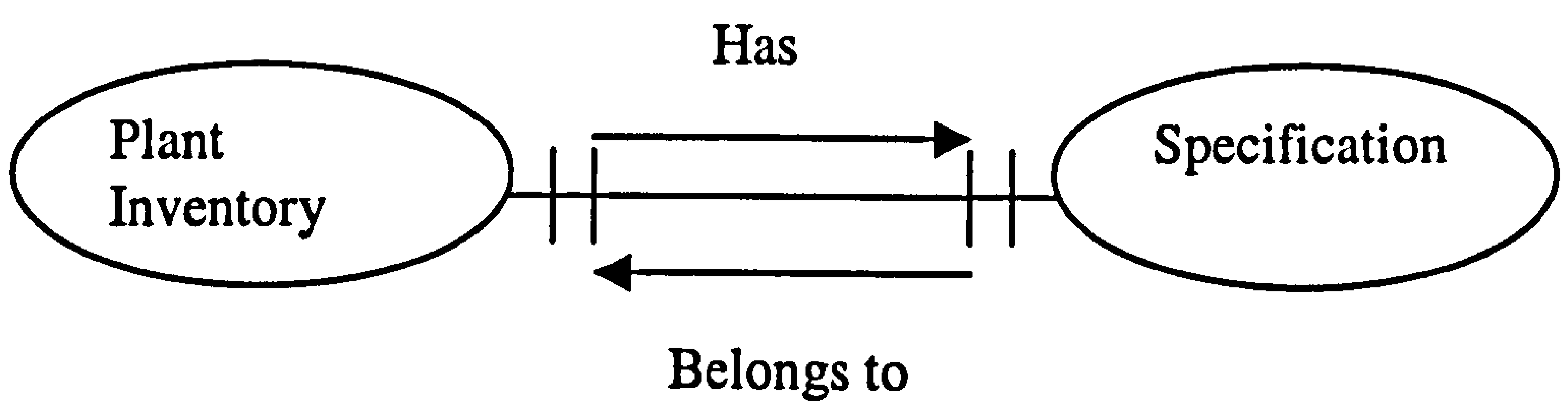
Figure 5.2: The Stages in Producing a Viable Database Schema



- **Plant Inventory – Specification Relationship**

Each plant item on the PLANT INVENTORY has one set of SPECIFICATIONS and each SPECIFICATION belongs to one plant item; hence, the One-to-One relationship. This relationship can be represented diagrammatically as follows:

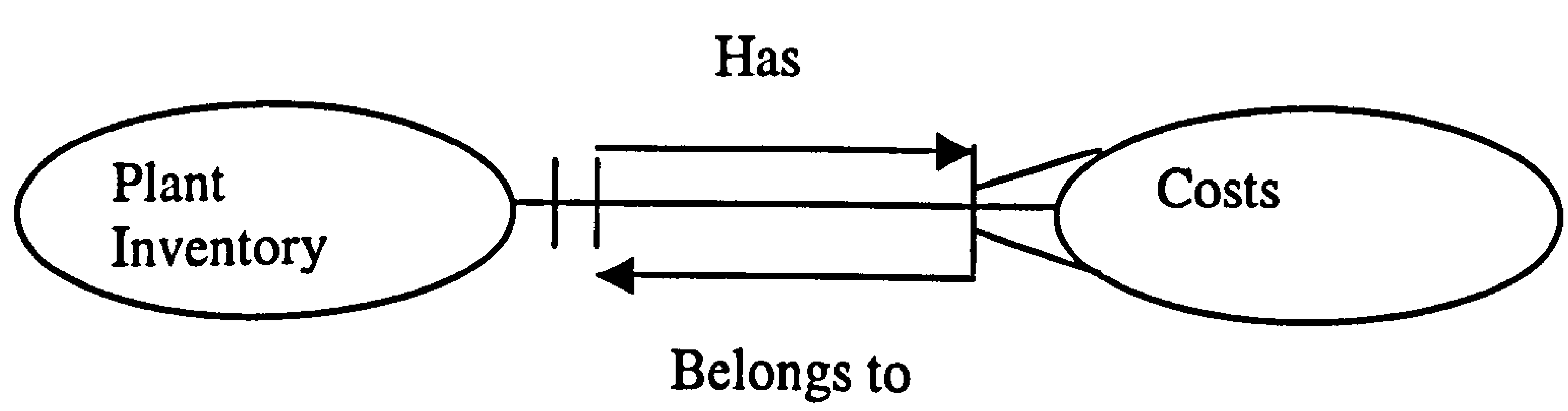
Figure 5.3: Plant Inventory-Specification One: One Relationship



- **Plant Inventory - Costs Relationship**

Each plant item on the PLANT INVENTORY has one or more COST(s) records and each COST record belongs to one plant item in the PLANT INVENTORY i.e. a One-to-Many relationship.

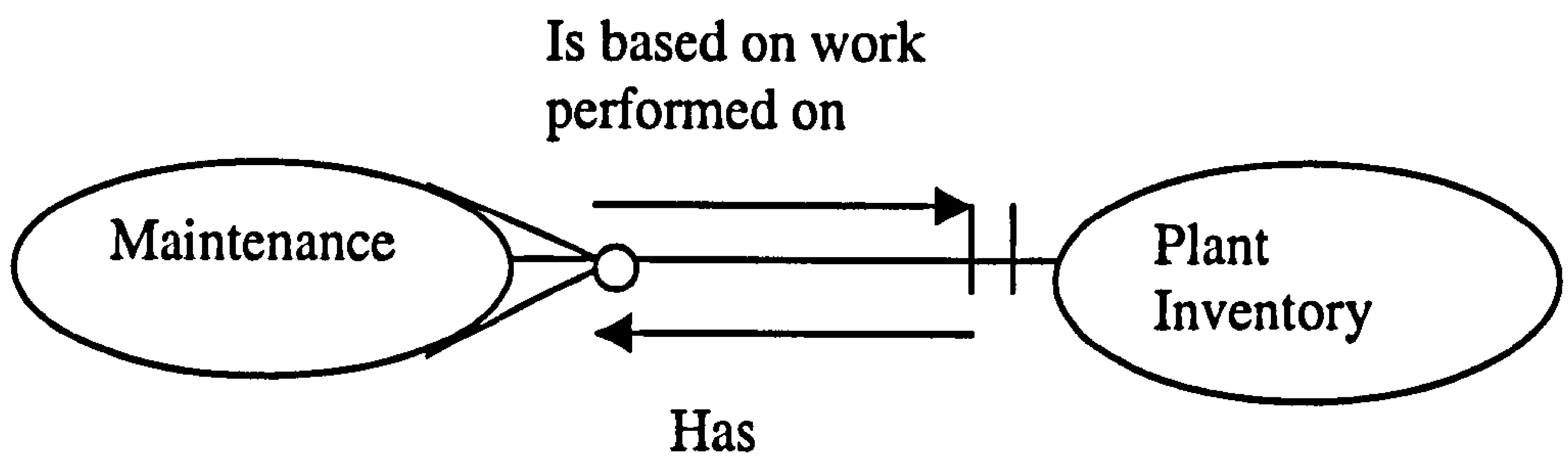
Figure 5.4: Plant Inventory-Costs One: Many Relationship



- **Plant Inventory – Maintenance Relationship**

Each plant item on the PLANT INVENTORY has zero or more MAINTENANCE records and each MAINTENANCE operation is carried out on a particular plant item in the PLANT INVENTORY. Thus a One-to-Many relationship exists.

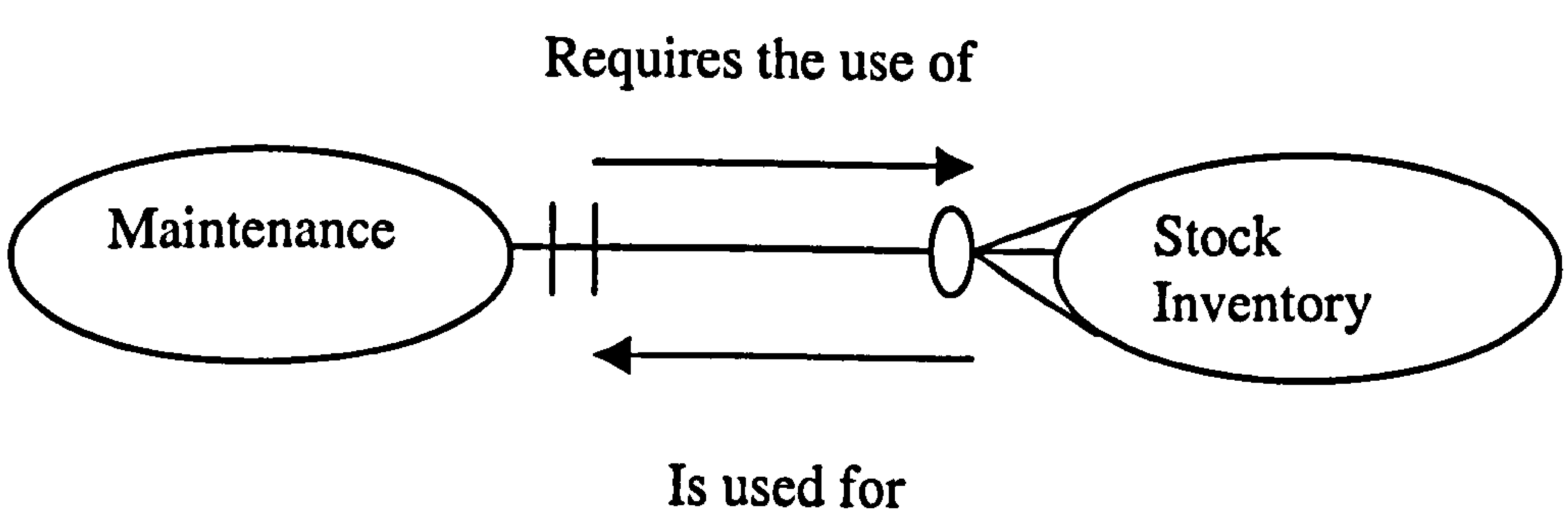
Figure 5.5: Plant Inventory-Maintenance One: Many Relationship



- **Maintenance – Stock Inventory Relationship**

Each plant item MAINTENANCE operation requires the use of zero or more parts from the STOCK INVENTORY and each part is contained within the STOCK INVENTORY. MAINTENANCE operation is carried out on a particular plant item in the PLANT INVENTORY. Therefore, a One-to-Many relationship exists.

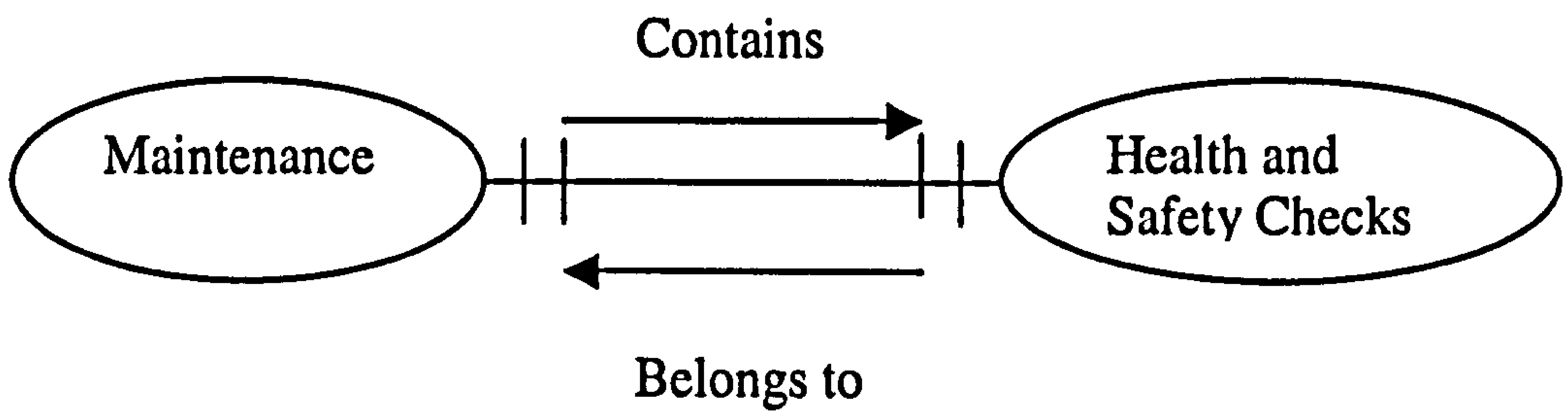
Figure 5.6: Maintenance - Stock Inventory One: Many Relationship



- **Maintenance - Health and Safety Checks Relationship**

Each plant item MAINTENANCE operation contains zero or one HEALTH AND SAFETY CHECK record and each HEALTH AND SAFETY CHECK belongs to one MAINTENANCE operation. This is thus a One-to-One relationship.

Figure 5.7: Maintenance - Health and Safety checks One: One Relationship



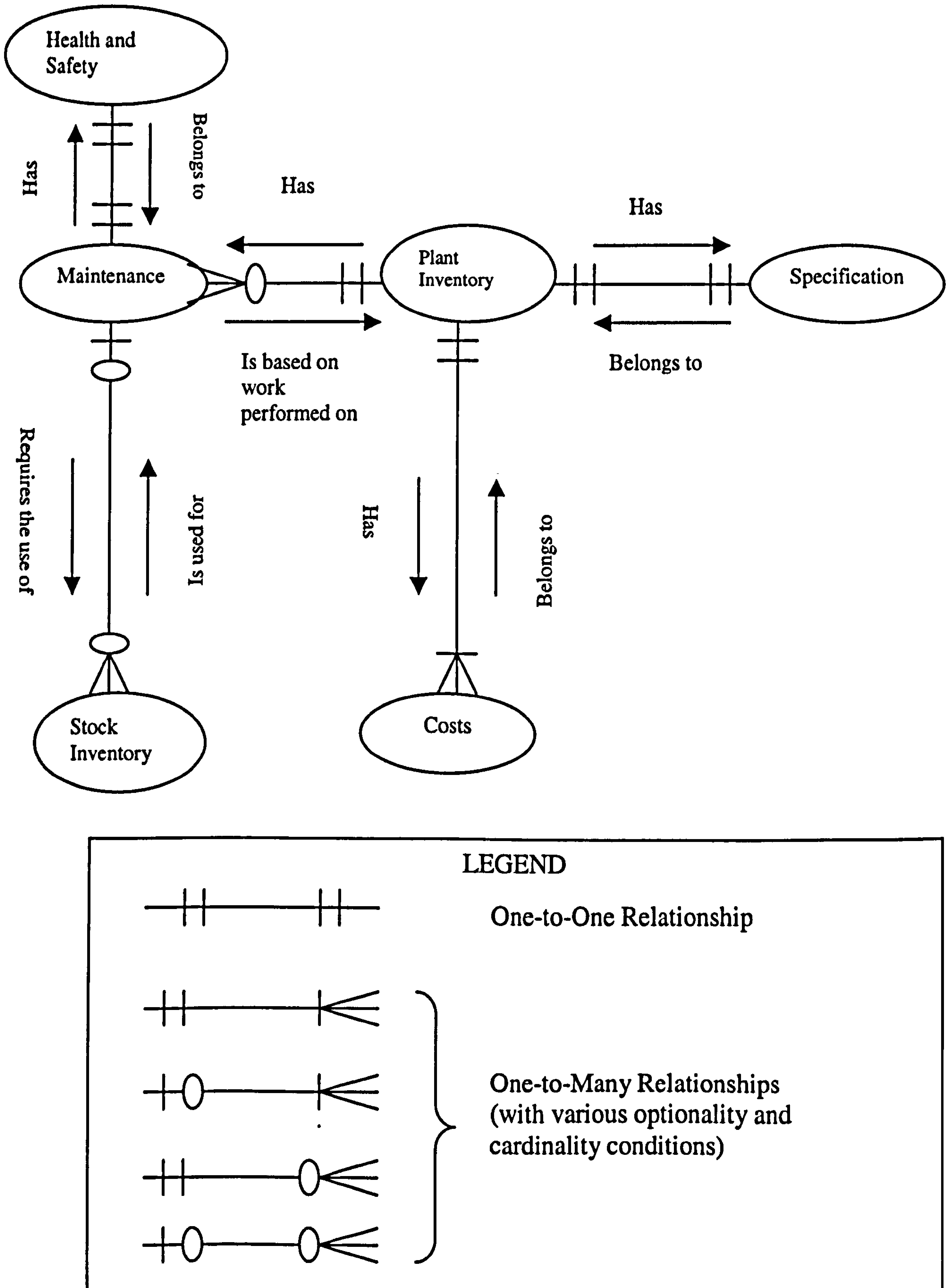
Thus there are five 'core' possible relationships identified within the entities of the database. Each relationship has minimum and maximum possibilities known in each case as the relationship's optionality and cardinality respectively. These properties define the structure of the entity-relationship model. Table 5.2 is a summary of the optionalities and cardinalities for the database.

Table 5.2: Summary of the Database Optionalities and Cardinalities

		Relationship Limits at BEGIN NODES	
S/No.	**Relationship**	**Optionality**	**Cardinality**
1.	Plant Inventory – Specification Relationship	1	1
2.	Specification – Plant Inventory Relationships	1	1
3.	Plant Inventory- Costs Relationship	1	1
4.	Costs - Plant Inventory Relationships	1	Many
5.	Plant Inventory – Maintenance Relationship	1	1
6.	Maintenance – Plant Inventory Relationship	0	Many
7.	Maintenance – Stock Inventory Relationship	0	1
8.	Stock Inventory – Maintenance Relationship	0	Many
9.	Maintenance – Health & Safety Check Relationship	1	1
10.	Health & Safety Check – Maintenance Relationship	1	1

Assembling all the relationships defined and incorporating all the conditions (optionalities and cardinalities) leads to the generation of the E-R model (Figure 5.8). The ER model constitutes the fundamental template for the RDBMS.

Figure 5.8: Entity-Relationship Model for the Off-highway Plant RDBMS



Creation of Attribute Lists

Every entity type on the E-R model contains a set of attributes that specifically describes the nature of each entry on the database. The attributes also help to define the join types and the referential integrity of the many databases within the RDBMS. The following Tables describe the selected attributes for the different entities of the database and the codes used to identify them. Table 5.3 gives a summary of the attribute numbers per entity type. Details of each attribute and the respective database codes are given in Appendix IV.

Table 5.3: Entity Types and Attribute Numbers of the RDBMS

Entity Type	Number of Attributes
Plant Inventory	18
Stock Inventory	6
Specification	10
Maintenance	25
Health and Safety Checks	18
Costs	14

SELECTION OF PRIMARY KEYS AND FOREIGN KEYS AND NORMALISATION OF THE SCHEMA

Assembling the six entities and all the initial attributes presented in Figures 5.2 to 5.7 results in an extended version of the E-R model, which contained information on the relationships between the entities. It also enabled the development of relationships between the primary keys and foreign keys. A primary key is an attribute or a group of attributes that uniquely identifies each entity in the entity type, and each record in the corresponding database table (Carter, 2000). No two records in a RDBMS are allowed to contain the same value of the primary key. Foreign keys, on the other hand, are used to show relationships. In a relationship between any two entities, the primary key in the first entity will also appear as the foreign key in the second entity.

Having produced a provisional set of table designs for the new database, the next step was to check for anomalies in the design by using the rules of normalisation. Three basic checks were applied. These are:

i) The First Normal Form (1NF) - which served to remove all repeating groups (attribute groups in the record that occurs over variable number of times in each record).

ii) The Second Normal Form (2NF) – which served to remove partial dependencies (all non-key attributes must be dependent on the whole or all of the primary key).

iii) The Third Normal Form (3NF) – which served to remove non-key dependencies (there should be no functional dependencies between non-key attributes).

Based on the procedure enumerated above, a database schema was produced for development on Microsoft Access 2000 Database (Figure 5.9). A detailed explanation of each code is given in Appendix III.

The schematic diagram in Figure 5.9 illustrates the relationships between the entity types and all attributes. The bold highlight and underlined attributes are the primary keys within each entity type, while the bold highlight (but not underlined) attributes represent the foreign keys to the associated entity type. Where two or more attributes are boldly highlighted and underlined within an entity type or relation, such attributes are referred to as composite primary keys of that entity type. A listing of the primary, foreign and composite keys selected for the off-highway plant information management RDBMS are given in Table 5.4.

Figure 5.9: Final Database Schema

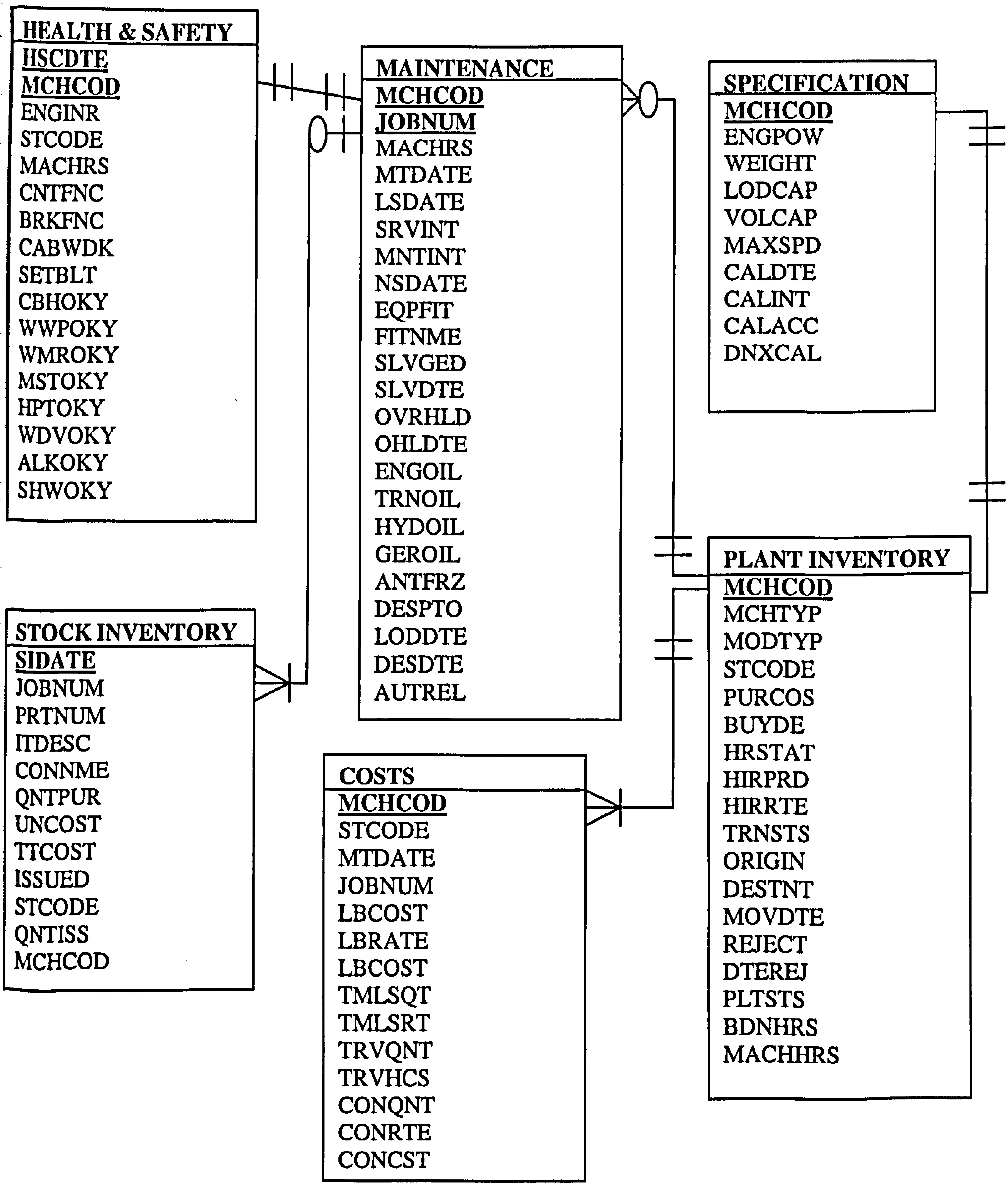


Table 5.4: Primary, Composite and Attribute Lists

S/No.	Entity Type	Primary Key	Foreign Key	Composite Key
1.	Plant Inventory	MCHCOD	MCHCOD	NIL
2.	Specification	MCHCOD	MCHCOD	NIL
3.	Maintenance	NIL	NIL	MCHCOD JOBNUM
4.	Health and Safety	HSCDTE	MCHCOD	NIL
5.	Stock Inventory	SIDATE	JOBNUM	NIL

FINAL E-R MODEL AND ENTRY/OUTPUT SCREENS

The final E-R model is shown in Figure 5.10. The model ensures that all referential integrity rules for relational database operations are enforced. The enforcement of referential integrity rules implies that the model does not permit duplication of data entry. However, the model also permits the use of the tables as forms, which facilitate the input, and viewing of data pertaining to a particular plant item in real time. Based on this model capability, entry of historical records into the database tables is significantly enhanced. Users may also use the forms to search for data by date of entry or other primary key parameters.

The RDBMS Data Entry and Interface Forms

A total of nine forms were developed for the RDBMS (see table 5.5). The first form represents the main user interface, while the next six forms (forms 2-7) provide access to RDBMS data update forms. The remaining forms (forms 8 and 9) allow user access to the MBMS and the reports menu of INTELLIPLANT respectively.

Figure 5.10: Final MS Access Entity –Relationship Model

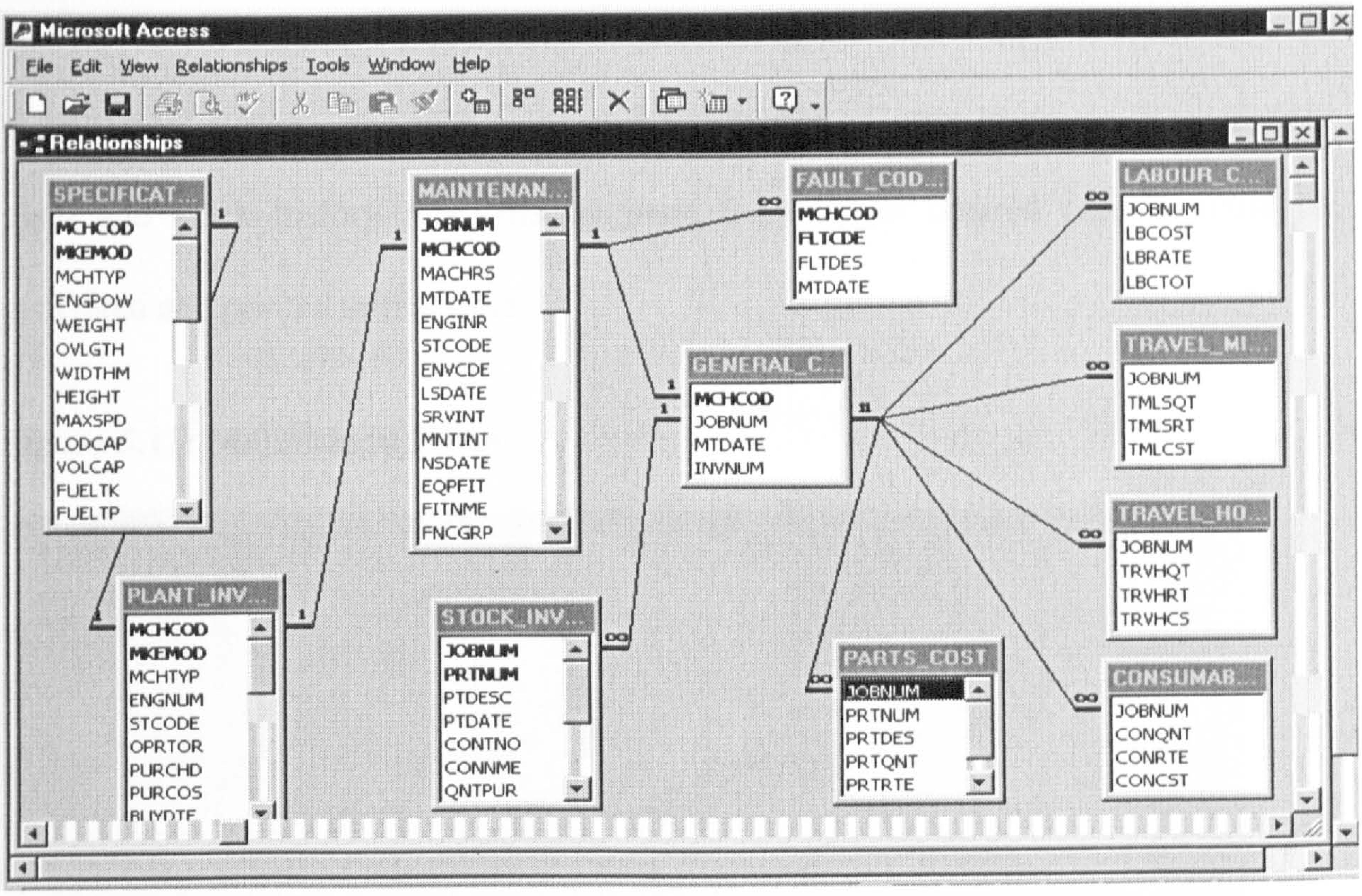


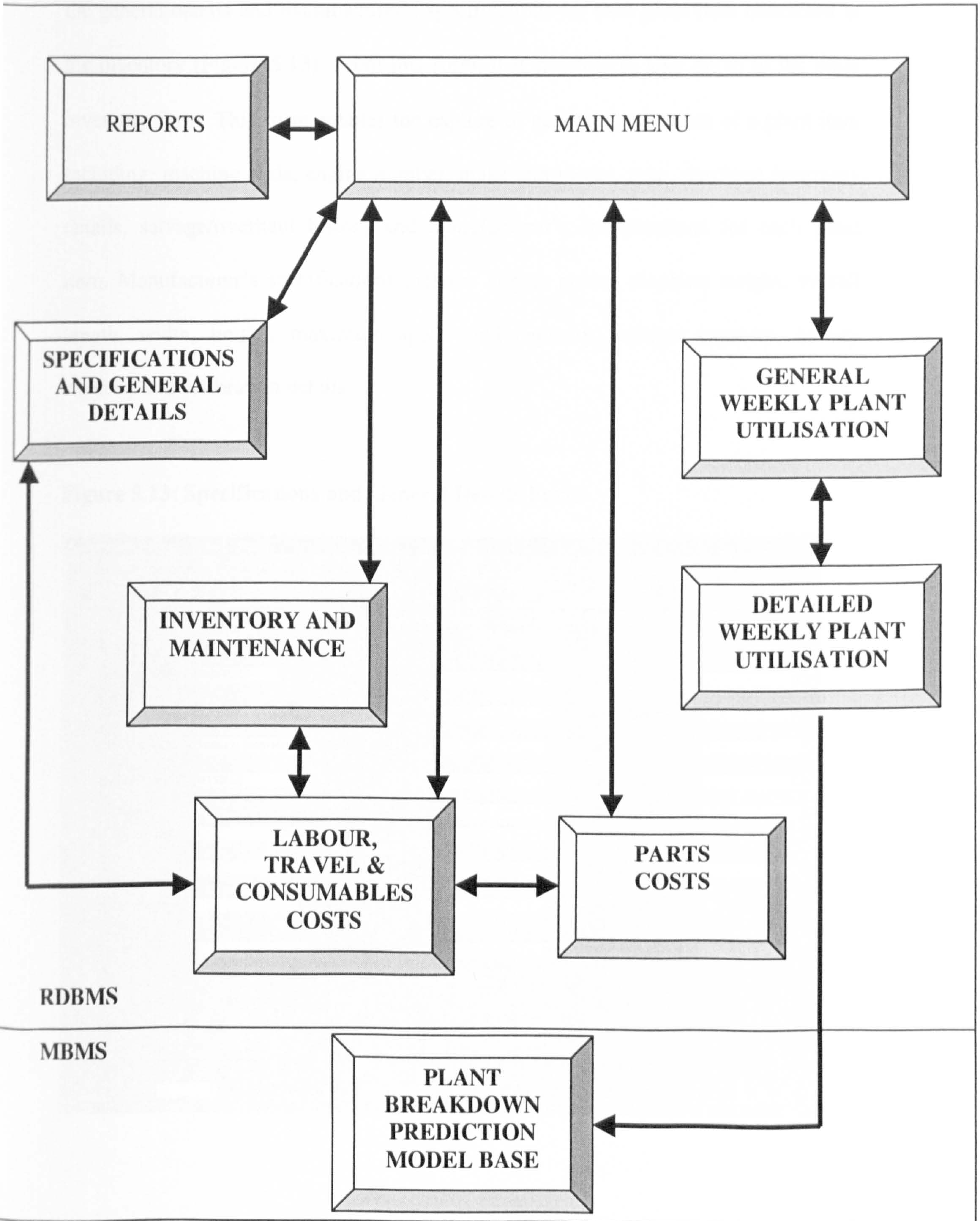
Table 5.5: Listing of Forms in INTELLIPLANT

S/No.	Form Title	Form Content
1.	Form1	Main Menu
2.	Form2	Specifications
3.	Form3	Inventory and Maintenance
4.	Form4	Labour, Travel Miles, Travel Hours and Consumables Costs
5.	Form5	Parts Costs
6.	Form6	General Weekly Utilisation Data
7.	Form7	Detail Weekly Utilisation Data
8.	Form8	Model Base
9.	Form9	Reports Menu

Main Menu Form

The main menu form represents the controlling user access interface of INTELLIPLANT. The form enables ease of navigation to all sections of INTELLIPLANT's RDBMS and MBMS (refer to Figure 5.11). The first three command buttons enable access to and the update of the machine's specifications,

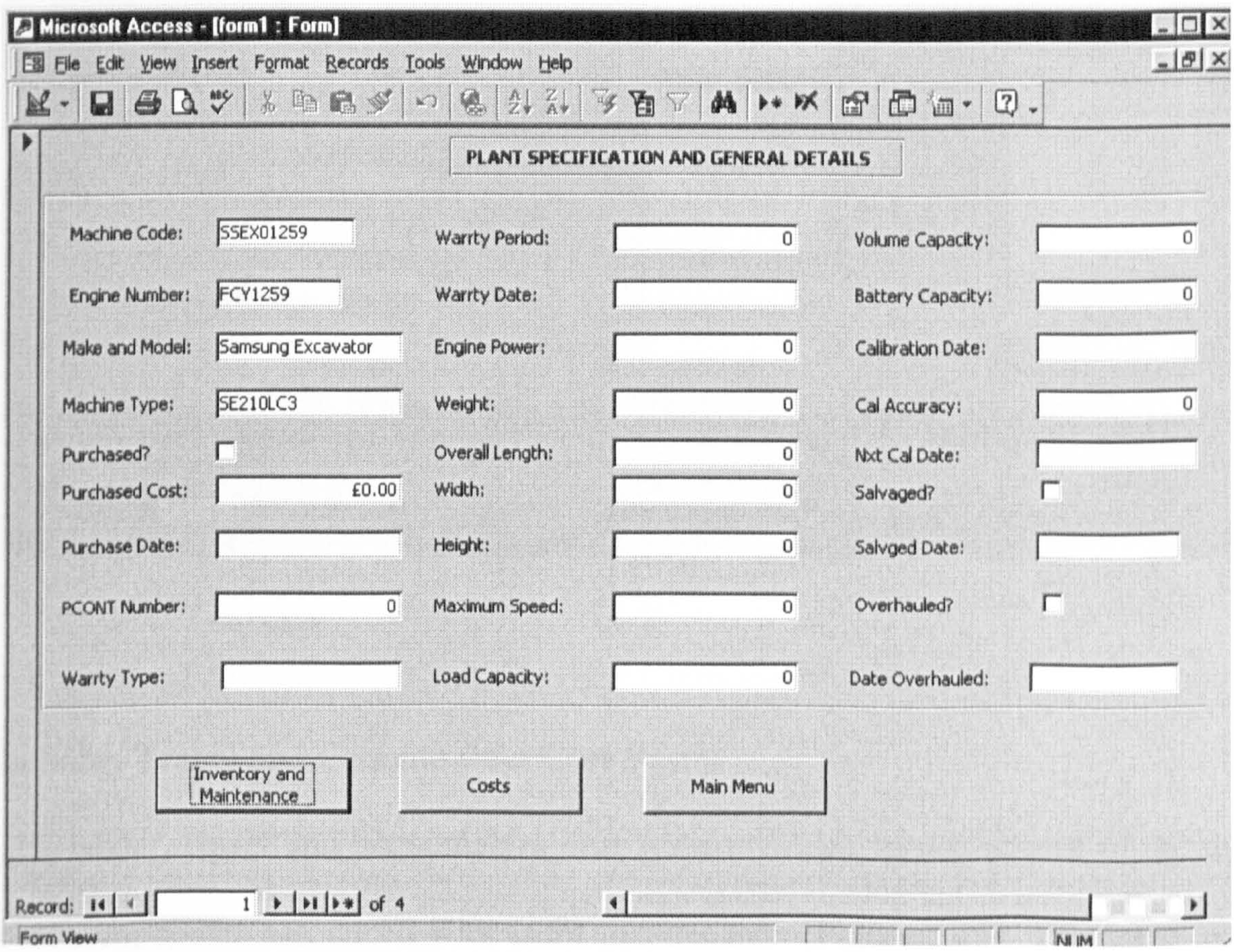
Figure 5.12: Navigation Structure of Forms in INTELLIPLANT



Specification and General Details Form

The specification and general details form provides the basic data entry interface for the general details and manufacturer's specifications for each plant item contained in the inventory (Figure 5.13). From this form, it is possible to also move to the plant inventory form. This form enables the capture of general details data of a plant item including: machine code, engine number, make and model, type, purchase /warranty details, salvage/overhaul history and manufacturer's specifications for each plant item. Manufacturer's specifications include: engine power, machine weight, overall length, width, height, maximum sped, load capacity, volume capacity, battery capacity and calibration details.

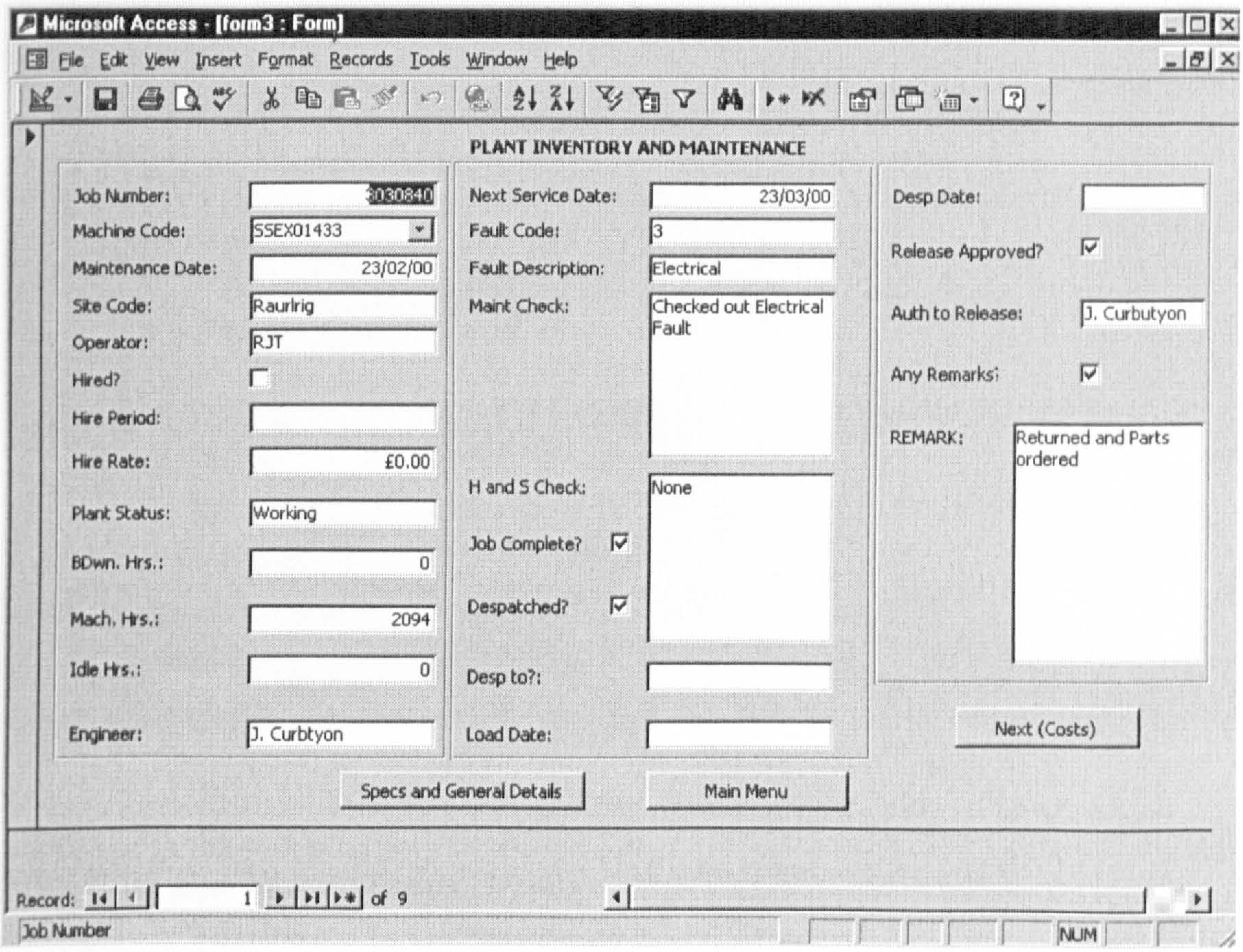
Figure 5.13: Specifications and General Details Form



Plant Inventory and Maintenance Forms

The plant inventory and maintenance forms allow inventory and maintenance data input/updates. Users can also input details of health and safety checks conducted on individual plant items through this form's interface (Figure 5.14). The design of the form facilitates navigation to two other forms. These are the specifications and general details form and the costs update form.

Figure 5.14: Plant Inventory and Maintenance Form

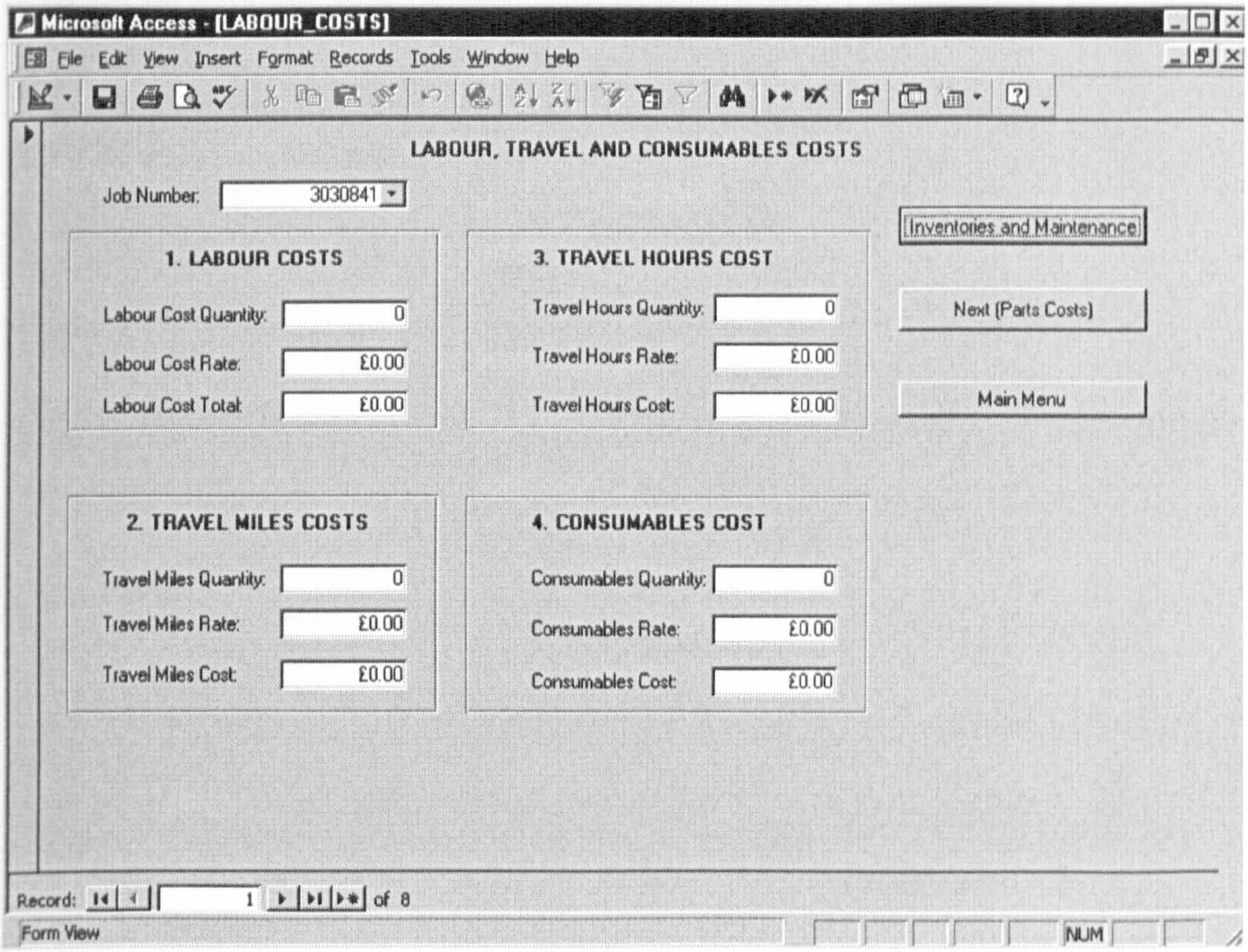


Labour, Travel and Consumables Cost Form

The labour, travel and consumables cost form provides instant access to the major cost components associated with plant maintenance (Figure 5.15). The form can be directly accessed from the main menu (for quicker access) or from the inventory and maintenance form. However, referential integrity rules between the 'plant inventory /

maintenance' and the 'cost' forms imply that 'cost' data must have corresponding data in the maintenance records. The form also provides a link to the parts cost update and inventories and maintenance forms.

Figure 5.15: Labour, Travel and Consumables Form

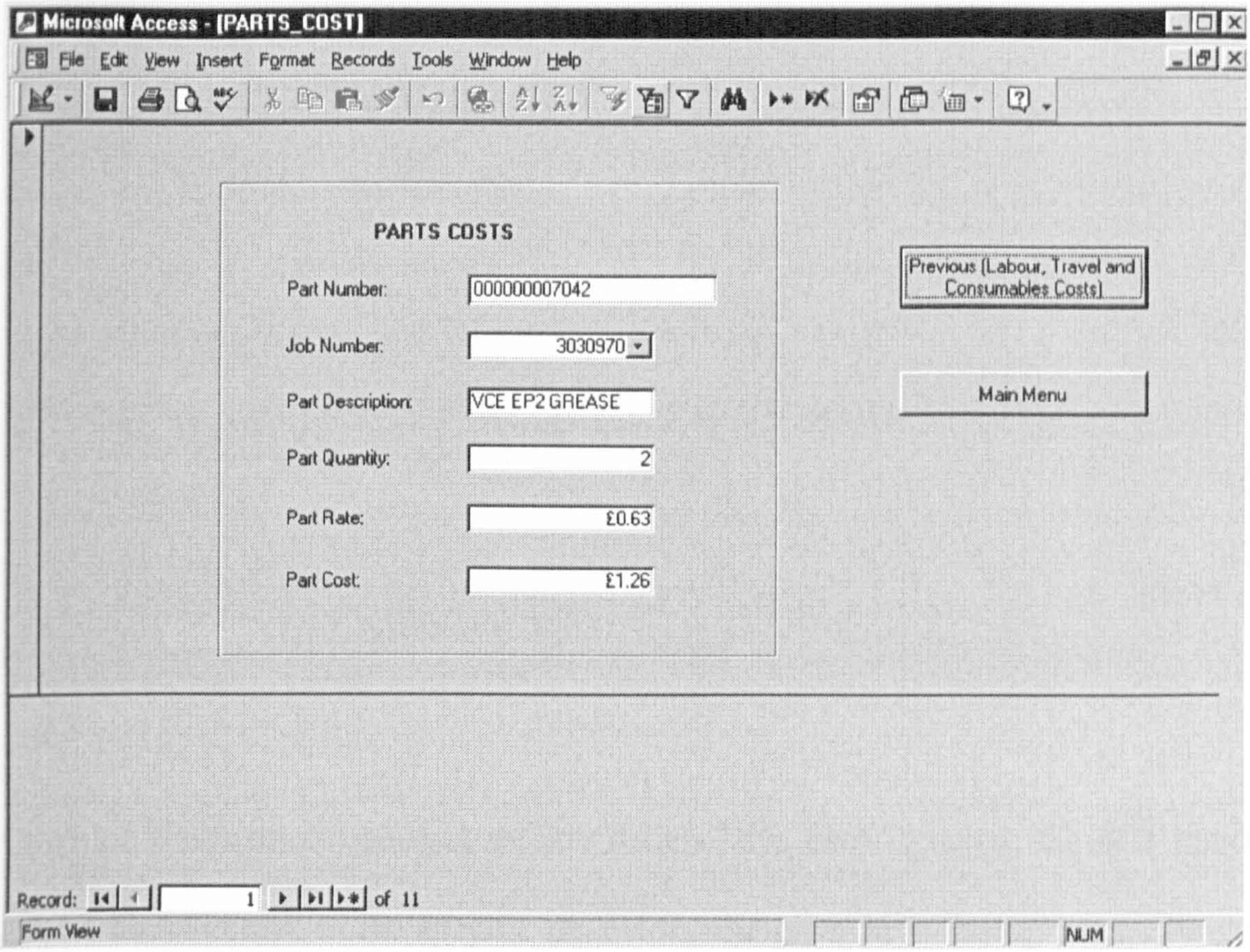


Parts Cost and Update Form

The cost of parts used and the stock inventory records are updated through this form. As illustrated in Figure 5.12, the form can only be accessed from the labour, travel and consumables cost form. This is because data update on the parts inventories/costs must be relative to the other jobs associated with a maintenance job. A sample layout of the form is shown in Figure 5.16.

The form also provides access to the labour; travel and consumables form in addition to granting access to the other sections of the RDBMS through the main menu.

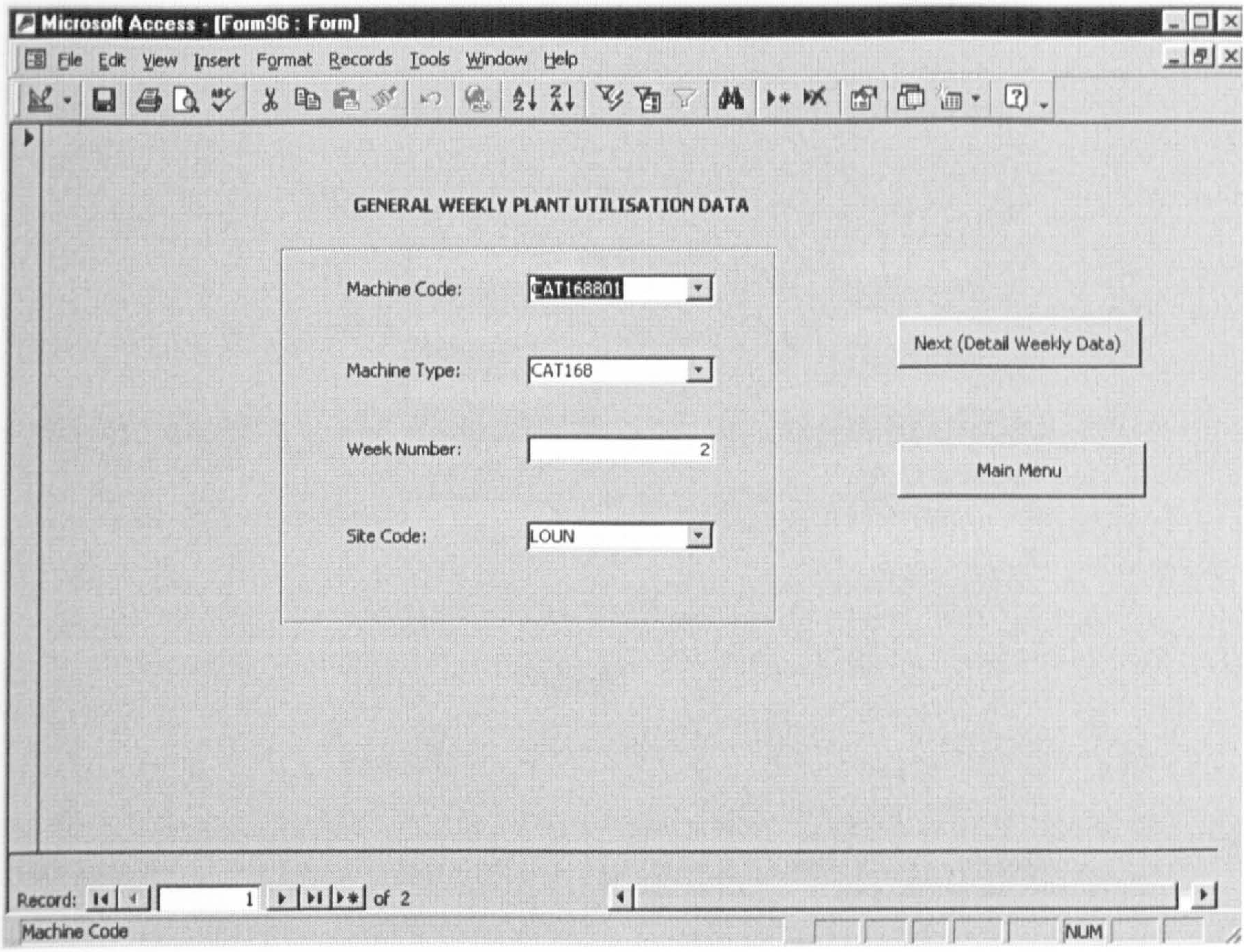
Figure 5.16: Parts Cost Form



General and Detail Weekly Plant Utilisation Data Update Form

This form enables users to gain access to the plant utilisation data update section of the RDBMS in order to capture detailed records of plant availability, utilisation and breakdown (Oloke and Edwards, 2001). The general utilisation details form (which is accessible from the main menu page) facilitates the specification of the machine code, machine type, week number and site code (Figure 5.17a).

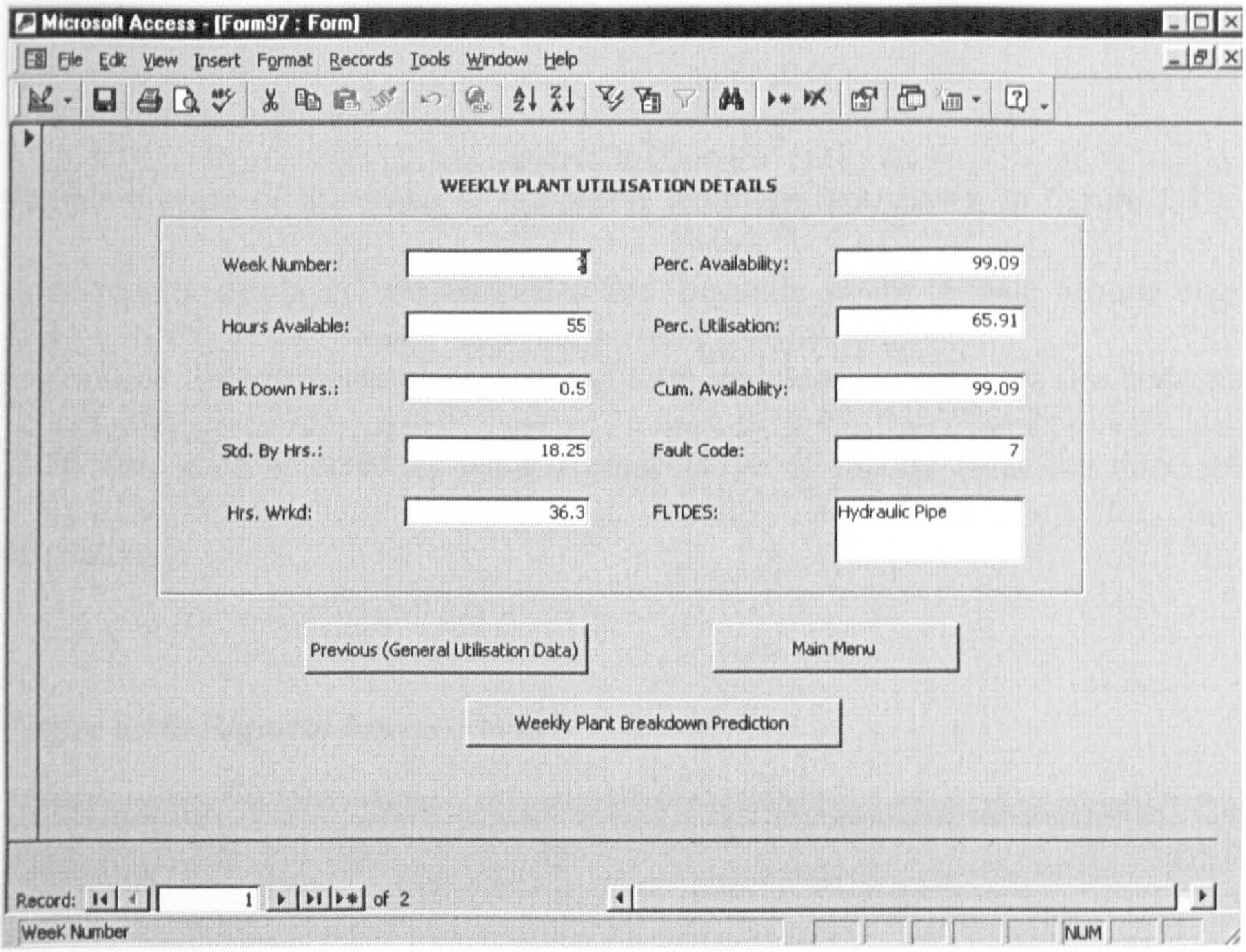
Figure 5.17a: General Weekly Plant Utilisation Data



Once the fields on the general weekly details have been updated, the user interface allows direct access to the specific details for the plant item during a specific week. Therefore, it is only possible to navigate from the general data section to the detailed data section or the main menu of the RDBMS. Detailed plant utilisation records captured include; plant breakdown, standby and worked hours (Figure 5.17b). Relevant percentages and faults recorded during breakdowns are also captured as appropriate (Figure 5.17b).

The weekly plant utilisation details form, therefore, allows navigation to general utilisation data, the main menu and the MBMS for weekly plant breakdown prediction.

Figure 5.17b: Weekly Plant Utilisation Details Form



Formulation of Queries and Design of Reports

The reports were designed so as to enable users to view the status of their fleet or a particular machine based on the most recent history records. The reports designed were based on queries developed using SQL. In all, about 25 queries were developed to enable INTELLIPLANT to generate real time plant history report sheets. The report sheets were grouped into three categories as follows:

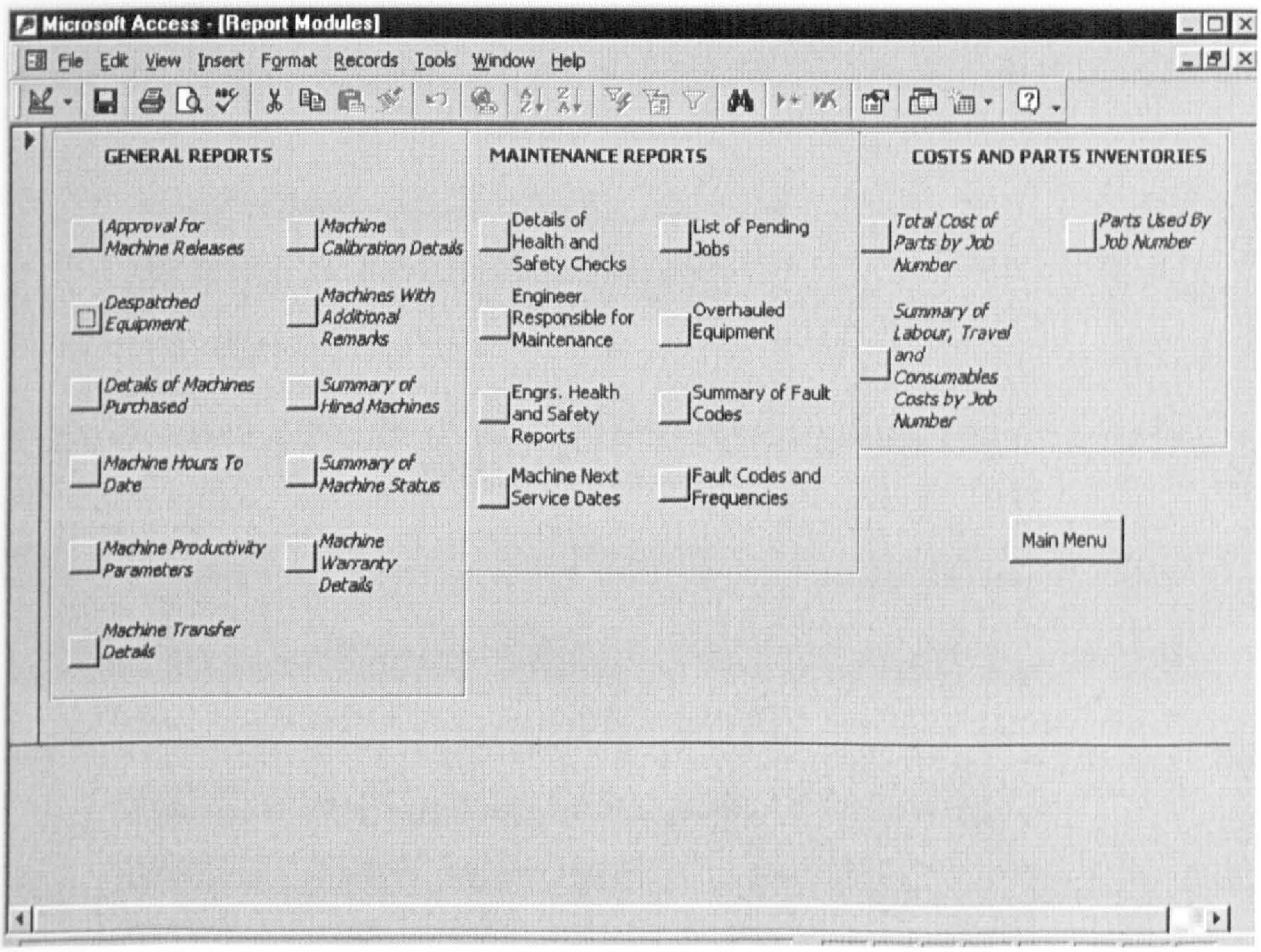
i) general reports – dealing with inventories and general remarks about machine status;

ii) maintenance reports – dealing with all aspects of fleet maintenance history including scheduling and planning; and

iii) costs and parts inventories - dealing with all elements of costs of maintenance, parts and inventory stocks.

Sample outputs of the some of the report templates are shown in Figure 5.19. The three reports displayed are templates for: machine hours to date report; engineer responsible for maintenance report; and total maintenance costs by site code report. They were each selected as being representative of reports from the three groups respectively.

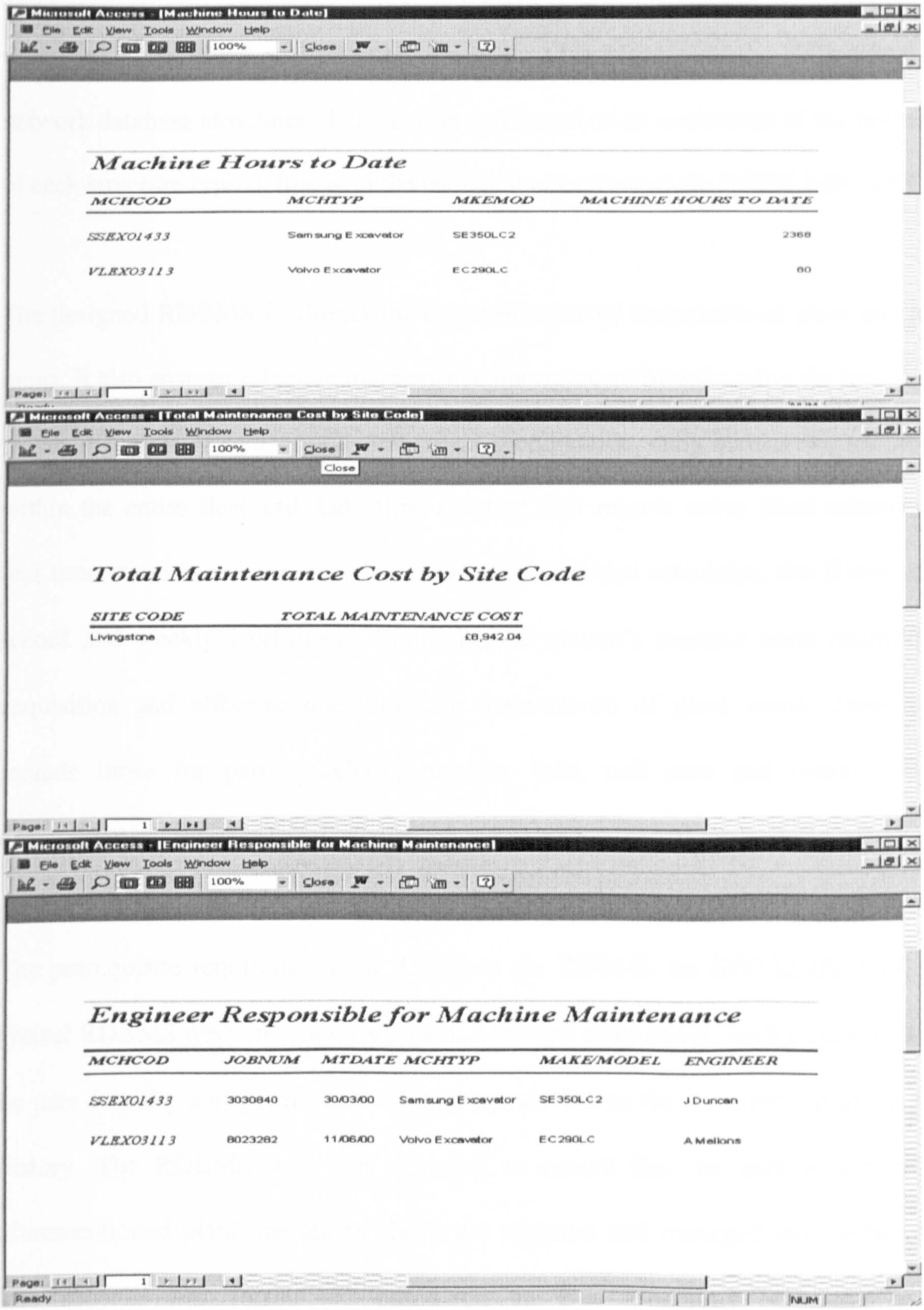
Figure 5.18: Reports Access Form



Figures 5.11 to 5.18 illustrated the user-friendly nature of the Graphical User Interface (GUI). This user-friendliness was one of the principal requirements expressed by practitioners during the field investigations. Also, the ease of navigation through the

database was greatly enhanced through an enforcement of referential integrity in the design of the RDBMS.

Figure 5.19: Sample Outputs from the Report Templates



SUMMARY

The approach to the development of the RDBMS as a data capture/report generation component for the intelligent off-highway plant information management system was described. A RDBMS was selected due to its advantages over the hierarchical and network database structures. This section was based on an evaluation of the properties of each structure type in line with the technical objectives of the INTELLIPLANT.

The designed RDBMS facilitates the documentation of inventories of plant and stock items. It also ensures effective maintenance management by enhancing the issuance of real time reports. These reports cover plant specification, daily breakdown summaries within the entire fleet and daily time sheets. Other reports cover plant maintenance real time status, servicing and maintenance records and schedules, site fitters' daily record and weekly worksheets. Similarly, the system's monitor costs incurred for acquisition and effective operation and maintenance of plant items. These costs include those for parts purchase, machine jobs, unit jobs and overall weekly expenditure.

The prerequisite requirements for designing the RDBMS for INTELLIPLANT as a typical RDBMS were rigorously pursued. Amongst other things, such a system should be user friendly and permit ease of data update due to the dynamic nature of plant history. The RDBMS was thus designed to ensure that the data related to the aforementioned plant operations above are captured and managed most effectively. The schema was formulated based on an E-R modelling technique and a normalisation of datasets. Input and output forms and reports were thus subsequently

evolved from the final E-R model using the Microsoft Access 2000 software. The form navigation and report generation capabilities of the RDBMS were greatly enhanced by the application of macros and SQL programming of the RDBMS. The reports designed were based on queries developed using SQL. About 25 queries were developed to enable INTELLIPLANT generate real time plant history report sheets.

In addition to the above-mentioned capabilities of the RDBMS, the system also provides a means of interface with the MBMS. The MBMS hosts the dynamic models for predicting plant breakdown events based on plant history data. Details of the development of the MBMS are discussed in subsequent sections of the thesis.

CHAPTER SIX: INTELLIPLANT - Historical Data Synthesis and Selection of Modelling Technique

INTRODUCTION

The main goal of successful project management is to satisfy client requirements, such that time, cost and quality constraints imposed by the contract documents are met (Nunnally, 2000). Achieving such normally involves the meticulous control of production processes and procedures, along with the selection and use of appropriate equipment (Sain and Quimby, 1996). Usually the project team will know the type and quality of work, desired production rates and the costs of various 'complementary' plant items before the works commence (Baldwin *et al*, 1995). This myriad of 'interwoven' variables is quintessential to the equipment selection process since the usage of inappropriate plant items can adversely affect project performance (Hendrickson, 2000).

In this chapter, a critical assessment of collected plant history data is undertaken. Such data includes plant utilisation, breakdown rates, maintenance costs and fault occurrence. Since emphasis is placed on plant IT management within industry, it is necessary to study the impact of these data on plant performance and project delivery.

The assessment of plant history data in this chapter took the form of descriptive statistical analyses. The analyses sought to determine any particular trends that may aid a model selection procedure for the development of plant breakdown prediction models. Therefore, established modelling procedures, which were considered relevant to the objectives of this study, were reviewed. The review sought to assess the suitability of each technique for modelling plant history data. Recommendations from other recent studies on plant history modelling techniques also complimented the selection of a suitable modelling technique.

The chapter concludes with a conceptual approach to modelling plant breakdown prediction using the time series analysis technique. Plant breakdown prediction modelling was selected due to the significant effect of breakdown events on plant utilisation and maintenance costs. Similarly, the time series analysis technique was considered suitable based on its merits over other multivariate techniques reviewed.

DESCRIPTION OF KEY PLANT PERFORMANCE PARAMETERS

The collation of plant history data helps plant managers to assess plant performance over a given period of time (Olomolaiye *et al*, 1998). Various records that monitor key performance parameters are required as plant items are engaged on various types of work (Edwards, 1999; Nunnally, 2000). These key parameters are: plant utilisation, plant breakdown, plant maintenance costs and fault analysis. Each parameter has its direct effect on plant productivity. However, a collective appraisal of their cumulative magnitudes or frequencies can help to significantly foster a greater understanding of each plant item's condition. Such an appraisal is therefore useful and can be preceded by an understanding of the effect of each parameter in detail. A brief description of each parameter is therefore given as follows.

Plant Utilisation

Plant utilisation history data reports upon on the actual amount of time a plant item was 'engaged in active production' as opposed to maximum availability. The data collected is usually expressed as either a percentage of maximum availability or recorded hours. This performance measure enables plant managers to readily gain additional insight into individual plant productivity (Hendrickson, 2000). Other performance parameters such as actual cycle time and production rate can also be computed as a function of plant utilisation (Sain and Quimby, 1996). Cycle time for is the time required by a mobile plant item (such as a dump truck) to complete one round trip when being utilised. The components of cycle time may also include load time, wait time, delay time, haul time and dump time (Lewis and Steinberg, 2001). The inclusion of these would depend on the type of plant item and/or activity under consideration and other site factors. Production rates are also measured as the volume of plant output, under given job conditions, per hour (Price, 1991). In addition, plant idle times and plant non-productivity (as a result of plant breakdown or scheduled maintenance works) can easily be assessed over a controlled period of time from the plant utilisation records. The statistics of plant breakdown and standby times can therefore also facilitate the measurement of plant productivity.

Plant Breakdown

Breakdown is defined as the state in which a plant item is temporarily or permanently unusable (Canter, 1993). Plant breakdown occurs as a result of malfunctioning of compartments (engine, hydraulics etc) or components within them (Penrose, 2000). For example, within an engine compartment, components include piston rings, filters, etc. Plant breakdown can also be caused by the absence of (or implementation of a poorly managed) fixed time-to-time maintenance programme (Wetzel, 1998; Edwards, 1999). Plant breakdown is an important plant performance parameter as its occurrence is positively correlated with other plant management parameters such as downtime and maintenance costs. However, increases in maintenance costs associated with breakdowns depend largely on the factors that caused the breakdown and the time it takes to rectify the faults and restore the plant item to site (Lewis and Steinberg, 2001). Downtime could also be 'natural' if used under a fixed time-to-time maintenance regime to conduct servicing.

Plant Maintenance Costs

Plant maintenance costs are generally grouped into two major categories as direct costs and indirect costs (Canter, 1993; Edwards, 1999; Edwards, Harris and McCaffer, 2002). Direct maintenance costs refer to those costs that are included in the maintenance budget of an equipment holding company and any items to be added during the budget's life of the (Nunnally, 2000; Edwards *et al*, 2000). Direct costs include those arising from historical records of: breakdown maintenance labour costs; planned maintenance labour costs; materials costs and fuel consumption costs; spares costs; and administrative, technical, equipment and other overhead costs. Furthermore, these components of direct maintenance costs can be further re-grouped into two sub-divisions of operational and administrative costs. Operational costs embrace maintenance labour, materials, fuels and spares costs. Conversely, administrative costs include other direct plant maintenance costs that are incurred on site (Edwards *et al*, 2000).

Indirect costs, on the other hand, refer to the plant maintenance costs that arise as a result of loss of production due to breakdown/repairs (Edwards *et al*, 2002; Edwards, 1999). Field investigations conducted as part of this study also confirmed that for plant hire firms, this might lead to loss of revenue via a reduction of budgeted utilisation (Oloke *et al*, 2001). Similarly, for plant owners, idle time of the work force constitute a major factor of indirect cost (Oloke and Edwards, 2002). Other indirect cost factors include loss of client goodwill and delays in contract execution (Edwards, *et al*, 1998).

Fault Occurrence

Fault occurrence is a phenomenon that grossly influences breakdown events, maintenance cost regimes and plant utilisation (Gerold, 1997). The phenomenon is dependant upon the various factors including type and age of plant item, amount of time worked, operating conditions, plant operator and so forth (Felton, 2000; Nasser, 2001). For example, a comparison can be made between a 3-year old tracked hydraulic excavator (with a 200-hour cumulative utilisation) and another 2-year old machine with a 300-hour cumulative utilisation. Track faults (for instance) are likely to be more frequent in the younger plant (2-year old plant) assuming they are both working under the same ideal conditions. However, this assumption may not necessarily hold validity if the older plant had been fitted with a new set of tracks after the first 200 hours. Also, faults could be mechanical or electrical and these classifications may also affect plant maintenance costs.

To this effect, every event of a plant breakdown is usually associated with a fault or series of faults. A critical investigation into this phenomenon is, therefore, important as a contribution to efforts aimed at improving plant management.

HISTORICAL DATA SYNTHESIS AND DESCRIPTIVE ANALYSIS

In order to proceed with the capture of historical data and carry out a data synthesis and descriptive analysis, the developed RDBMS of INTELLIPLANT was used to collect historical data. Plant history data was collected over a 12-month period for various plant items engaged in several off-highway applications across the UK. Plant items included: hydraulic tracked excavators, wheel loaders and rigid dump trucks manufactured by Caterpillar, Samsung and Volvo Construction Equipment. Due to the myriad of plant management systems, some data where recorded monthly, while others weekly. The details of plant type, model, and number investigated are given in Table 6.1. History data from a total of 349 plant items were utilised for the analyses. These were supplied by three collaborating organisations. The first is a manufacturer, the second is mining contractor, and the third is an independent consultant collecting data on various plant items for use by the UK Ministry of Defence. Various types of descriptive analyses were conducted on the respective history data of the plant items. These were with the objectives of investigating:

- plant model faults frequencies;
- plant breakdown as a function of fault occurrence;
- plant history utilisation as a function of fault frequency; and
- plant utilisation and breakdown time analysis.

The plant model fault frequency analysis enabled the identification of the most frequent faults occurring amongst the plant types (models) investigated. Results from these constituted the basis under which weightings could be assigned to each fault type used in the breakdown prediction model. Similarly, the investigation of plant breakdown events as a function of fault occurrence facilitated an understanding of: predominantly occurring faults that lead to plant breakdown and the average magnitude of breakdown durations based on specific faults.

Table 6.1: Details of Plant Items Investigated and the Investigations Conducted

S/No.	Plant Type	Manufacturer	Model	Number	Data Type
1.	Hydraulic Excavator	Samsung	SE130LC-3	106	Monthly
			SE210LC-3	27	"
			SE240LC-3	10	"
			SE280LC-2	18	"
			SE350LC-2	16	"
			SE450LC-2	8	"
		Volvo	EC140LC	49	"
			EC210LC	48	"
			EC240LC	13	"
			EC290LC	10	"
			EC360LC	20	"
			EC460LC	5	"
		Caterpillar	CAT 311B	2	Weekly
			CAT 375	3	"
2.	Wheel Loader	Caterpillar	CAT 908	6	"
			CAT 944D	8	"
3.	Backhoe-Loader	Caterpillar	CAT 446B	3	"
4.	Off-Highway Hauler	Caterpillar	CAT 777D	5	"

The plant history utilisation as a function of fault frequency analysis was conducted in order to determine the existence of any relationship between the occurrence of faults and the level of plant utilisation. Also, plant utilisation and breakdown time was investigated to further explore this hypothesis. It was anticipated that these analyses would form a basis upon which plant utilisation may be included as a predictor variable in the proposed plant breakdown prediction model.

The descriptive analysis of historical data conducted during this research was based on the nature of data available. For instance, historical data that were available and collected on the Samsung and Volvo hydraulic excavators were based on a 12-month (monthly) observation of fault occurrences and associated rectification costs on the range of models shown in Table 6.1. Descriptive analysis on these data enabled an appraisal of fault frequencies and associated costs related to the rectification of those faults. This was to gain a better understanding of the data and to facilitate data modelling of plant breakdown prediction.

On the other hand, however, historical data obtained on the Caterpillar range of plant models (Table 6.1) were weekly observations of plant breakdown, standby and utilisation times over a 12-month period. These were based on an average of 50-week annual periods. The data also contained information on factors that affect efficient plant utilisation on a weekly basis. Such factors include fault occurrence, plant off-hire times, general service times and environmental (site) factors. It was envisaged that all these factors could affect plant breakdown and also impact production rates. Therefore, the modelling of the plant breakdown phenomenon as a way of predicting its occurrence and duration is quintessential. In addition, it would also be necessary to isolate the plant items by type in order to model their historical data as distinct entities.

However, in the classification of plant items and modelling their history data for plant breakdown prediction; plant 'age' and 'hours of operation' cannot just constitute the basis. Rather, the analysis of the percentage of breakdown time in relation to their rates of utilisation (under similar working conditions) proved to be a more formidable approach for classifying plant items and modelling historical data. This approach also helped in assessing the possibility of aggregating the historical data set from different plant items for further analysis.

The descriptive analyses results are discussed under three major classifications. These are: (i) plant model average breakdown, standby and utilisation frequencies; (ii) plant maintenance costs as a function of individual faults; and (iii) plant breakdown time as a function of fault occurrence.

Average Breakdown, Standby and Utilisation Frequencies

Average plant breakdown, standby and utilisation time data analysed are based on the historical data of 27 different Caterpillar plant items. Similar data corresponding to the Volvo and Samsung range of plant items were unavailable from the collaborating institutions. The Caterpillar equipment investigated comprise of 5 hydraulic excavators, 14 wheel loaders, 3 backhoe-loaders and 5 off-highway haulers. The machine models and specific numbers of each model are given in Table 6.1. This analysis facilitated a better understanding of the general conditions of the plant items themselves. All the weekly data collected over the 50-week period were computed as average annual frequencies of breakdown, standby and utilisation for each plant item. Comparisons between the individual models of the same plant type (working under similar conditions) were then made. Subsequently, comparative analyses of the performance characteristics of plant items were also carried out. Summary frequency statistics for all the plant items are given in Table 6.2.

Table 6.2: Frequency Statistics of Plant Breakdown, Standby and Utilisation

Plant Type	Average Percentage Breakdown Time (%)	Average Percentage Utilisation Time (%)	Average Percentage Standby Time (%)
Wheel Loaders			
CAT 908	4.94	69.86	25.21
CAT 994D	7.62	64.69	35.37
Average for Wheel Loaders	**6.28**	**64.69**	**30.29**
Backhoe-Loader			
CAT 446B	3.97	62.51	33.52
Average for Backhoe-Loader	**3.97**	**62.51**	**33.52**
Hydraulic Excavators			
CAT 311B	3.14	70.35	26.52
CAT 375	3.10	65.47	31.42
Average for Hydraulic Excavators	**3.12**	**67.91**	**28.97**
Off-Highway Hauler			
CAT 777D	6.74	77.4	16.74
Average Off-Highway Hauler	**6.74**	**77.4**	**16.74**
OVERALL MEANS	**4.92**	**67.57**	**28.13**

It was observed that the plant items were actively engaged over the study period based on the result of the overall mean utilisation percentage of 67.57. Similarly, the mean frequency of stand-bys amounted to 28.13 percent and breakdown time frequency was 4.92 percent. Therefore, assuming that there were no standby times, the results obtained indicate that the plant items would have probably been able to function for approximately 93 percent of the availability while experiencing breakdowns for about 7 percent. This result reveals a substantially high reliability level of performance for all the plant items. The finding also indicates that a relatively 'high quality' operation and maintenance strategy was implemented. The results of the comparative analyses are given in Table 6.3. The implication of this level of percentage breakdown on project performance is demonstrated as follows.

Wheel Loader CAT 908 Model

For the 6 CAT 908 wheel loaders, it was observed that most of the plant items, except the CAT 908 (2) were utilised over 67 percent of their availability. Although CAT 908 (5) had the maximum breakdown frequency of 11.79 percent, comparing the breakdown frequencies of all the models in relation to their utilisation frequencies, it may be inferred that CAT 908 (2) had the poorest performance output, while CAT 908 (6) appeared to be the best.

Wheel Loader CAT 994D Model

A similar assessment for the 8 CAT 994D wheel loaders showed that CAT 994D (2) seemed to have had the worst performance level, while CAT 994D (6) had the best. On the average, historical data from the 14 wheel loaders indicated a 6.28 percent breakdown, 64.69 percent utilisation and 20.29 percent standby time.

Backhoe Loader CAT 446B Model

In the case of the CAT 446B backhoe-loaders, the performance statistics of the 3 plant items reveal that CAT 446B (3) had the best performance statistics, with the minimum frequency of breakdowns. CAT 446B (2) on the other hand showed the poorest performance. Average backhoe-loader breakdown percentage frequency was computed as 3.97 percent, while utilisation and standby frequencies were computed as 62.51 and 3.97 percent respectively. This again is indicative of a fairly reasonable level of utilisation of the plant items.

Table 6.3: Various Model Results

		Percentage	
Item	**Breakdown (%)**	**Utilisation (%)**	**Standby (%)**
CAT 994 (1)	7.08	77.12	15.8
CAT 908 (2)	3.15	24.15	72.70
CAT 908 (3)	3.42	67.92	28.66
CAT 908 (4)	3.41	80.21	16.38
CAT 908 (5)	11.79	78.90	9.31
CAT 908 (6)	0.77	90.83	8.40
CAT 994D (1)	12.01	67.08	20.91
CAT 994D (2)	20.07	26.79	73.21
CAT 994D (3)	6.30	66.04	27.66
CAT 994D (4)	5.92	46.08	48.00
CAT 994D (5)	3.97	68.41	27.62
CAT 994D (6)	2.80	69.70	27.50
CAT 994D (7)	3.90	66.70	29.40
CAT 994D (8)	5.99	65.35	28.66
CAT 446B (1)	2.00	55.64	42.36
CAT 446B (2)	7.21	54.54	38.25
CAT 446B (3)	2.70	77.34	19.96
CAT 311B (1)	3.47	83.70	12.83
CAT 311B (2)	2.80	57.00	40.20
CAT 375 (1)	0.75	77.22	22.03
CAT 375 (2)	3.76	60.81	35.43
CAT 375 (3)	4.80	58.39	36.81
CAT 777D (1)	6.30	77.60	16.10
CAT 777D (2)	6.45	78.15	15.40
CAT 777D (3)	10.03	73.78	16.19
CAT 777D (4)	6.09	79.51	20.49
CAT 777D (5)	4.83	79.65	15.52

Hydraulic Excavator CAT 311B Model

Historical data from two different models of hydraulic excavators were analysed under this segment of the investigations. These were 2 CAT 311B models and 3 CAT 375 models. Results of the parameter frequency analysis of the CAT 311B models showed that the CAT 311B (1) had the best statistics.

Hydraulic Excavator CAT 375 Model

For the CAT 375 models, CAT 375 (1) gave the best performance having recorded the least breakdown frequency and the highest utilisation frequency. Average statistics reveal that all the 5 excavators encountered 3.12 percent breakdown levels, while utilisation and standby percentages stood at 67.91 and 28.97 percent respectively.

Off Highway Hauler CAT 777D Model

Five items of CAT 777D off-highway haulers were analysed. These range of plant items showed the closest performance statistics in terms of utilisation. A critical observation of their historical data over the study period revealed that stand by times were averagely below 17 percent, while breakdown frequency was about 6.74 percent. These statistics mean that the off-highway haulers were utilised at an overage of 77.74 percent of the times they were available on site. However, CAT 777D (5) appeared to be the most efficient hauler recording the least breakdown frequency of 4.83 percent at an utilisation rate that exceeded the average for all the plant items observed.

Application of the Plant Performance Statistics

The performance statistics conducted on the historical dataset of the different plant items has helped to ascertain the reliability of the plant items. The result of the performance evaluations revealed the average plant breakdown and utilisation levels, thereby indicating the relative extents the plant items have been utilised without breakdowns. This is a good indicator of the 'fitness' of the plant items.

Further investigations were however required in order to examine the analysis of the faults that cause the aforementioned breakdowns. Specifically, a frequency analysis of the faults as they affect plant breakdown occurrence and associated maintenance costs were investigated.

Plant Maintenance Costs as a Function of Faults

A positive linearly dependent relationship may be said to exist between plant faults and breakdown. This was because when a plant item develops faults, plant breakdown will invariably result. Such a relationship may also be said to exist between plant breakdown and maintenance costs. The justification for this is that an associated direct or indirect maintenance cost will be required to restore the plant item to full operational working order after a breakdown (Oloke and Edwards, 2002b). The magnitude of this cost however depends on the nature of fault or faults developed.

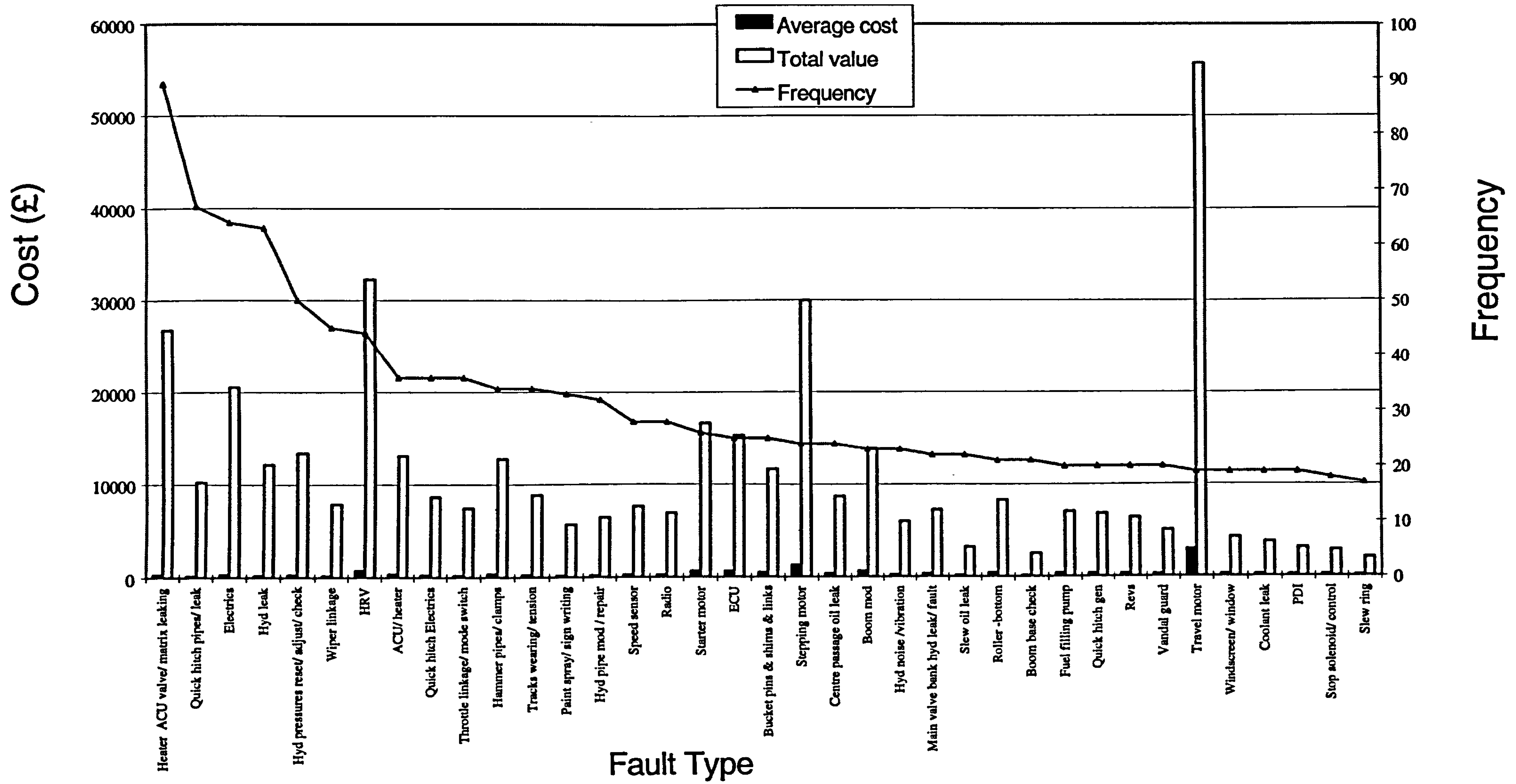
The 12-month (monthly) historical data collected on the 185 Samsung and the 145 Volvo hydraulic excavators were analysed to study fault occurrence events and the resultant rectification costs. Details of plant breakdown time associated with these fault occurrences were not included in the original dataset as emphasis was to determine fault frequencies on the plant items. However, a frequency analysis of the faults and the respective costs facilitated the process of fault classification for the purposes of modelling plant breakdown prediction. Table 6.4 gives the details of the faults and frequencies observed including the average and total costs of rectification based on the 330 plant items, while Figure 6.1 shows a graphical representation of the relationship between the observed variables.

An important observation is the fact that plant fault frequencies do not necessarily determine the level of associated rectification/maintenance costs. For example, faults such as heater/air conditioning unit (ACU) valve/ matrix leakage occurred with the highest frequency of 89 observations. These faults attracted a total value of £26,754.00 as associated maintenance cost. On the other hand, a relatively less frequently occurring fault such as travel motor breakdown with frequency of 19 observations had a total maintenance cost value of £55,671.99; a value, which was the highest for all faults observed. This is because travel motor servicing or replacement costs are much higher than those for heater/air conditioning units (Gerald, 1997; Wetzel, 1998). This is due to the high cost of replacement components. Therefore, in order to utilise fault occurrence as an independent variable for plant breakdown prediction, the assigning of 'weights' to individual plant faults was therefore, not based on the cost of rectifying the fault. Rather the frequency with which the faults were occurring was adjudged to be a more realistic basis.

Table 6.4: Observed Range of Faults and Associated Costs

S/No	Fault	Average cost (£)	Total value (£)	Frequency of occurrence (No.)
(a)	(b)	(c)	(d)	(e)
1.	Heater ACU valve/ matrix leaking	300.61	26754	89
2.	Quick hitch pipes/ leak	152.69	10229.90	67
3.	Electrical faults	321.29	20562.32	64
4.	Hydraulic leak	193.51	12191.23	63
5.	Hydraulic pressures reset, adjust or check	267.46	13372.79	50
6.	Windscreen wiper linkage	175.37	7891.55	45
7.	Hose rupture valve	733.21	32261.03	44
8.	ACU/ heater general faults	363.74	13094.55	36
9.	Quick hitch electrics	240.74	8666.80	36
10.	Throttle linkage & mode switch	206.83	7445.78	36
11.	Hammer pipes or clamps	375.97	12782.95	34
12.	Tracks wearing, track tension	260.39	8853.17	34
13.	Paint spray or sign writing	172.00	5676.07	33
14.	Hydraulic pipe mod or repair	201.29	6441.13	32
15.	Engine speed sensor	271.83	7611.34	28
16.	Radio and aerial	246.37	6898.32	28
17.	Starter motor	639.54	16627.94	26
18.	Electronic control unit	612.94	15323.45	25
19.	Bucket pins, shims & links	466.91	11672.87	25
20.	Stepping motor	1246.80	29923.09	24
21.	Centre passage oil leak	362.99	8711.65	24
22.	Boom mod	602.57	13859.07	23
23.	Hydraulic noise or vibration	261.72	6019.50	23
24.	Main valve bank hydraulic leak or fault	329.60	7251.14	22
25.	Slew ring oil leak	146.54	3223.96	22
26.	Bottom track roller	396.67	8330.07	21
27.	Boom base check	119.26	2504.36	21
28.	Fuel filling pump	351.48	7029.52	20
29.	Quick hitch general faults	341.55	6831.01	20
30.	Erratic revs/transmission	320.40	6407.95	20
31.	Vandal guards/final drive	252.29	5045.73	20
32.	Travel motor	2930.10	55671.99	19
33.	Windscreen or window	225.02	4275	19
34.	Coolant leak	196.64	3736.25	19
35.	PDI/steering ram	162.84	3094.00	19
36.	Stop solenoid or control	158.96	2861.26	18
37.	Slew ring general faults	119.51	2031.59	17
38.	Battery and associated parts	410.70	6571.24	16

Figure 6.1: Fault Frequencies, Average and Total Costs



However, an analysis of plant breakdown time as function of the fault occurrence was also made in order to facilitate a more holistic scenario of the influence of faults on breakdown events.

Plant Breakdown Time as a Function of Fault Occurrence

A 'best performance' criterion was set up for the selection of plant items for further analysis. The criterion involved the definition of plant items with the least breakdown/utilisation ratio as those with the 'best performance' (Penrose, 2000). The criterion was envisaged to lead to the selection of the plant items with the highest reliability within the sample set. The six plant items identified with 'best performance' characteristics were analysed for plant breakdown time due to occurrence of specific faults as a means of further investigating the influence of fault occurrence on plant breakdown time. The influences of percentage utilisation and standby times (as probable additional variables for predicting plant breakdown percentage) were also investigated. Details of the investigated plant items are as given in Table 6.5.

Table 6.5: Selected Plant items for Fault/Breakdown Analysis

S/No.	Plant Type	Model/Model Serial No.
1.	Wheel Loader	CAT 908 (6)
2.	Wheel Loader	CAT 994D (6)
3.	Backhoe Loader	CAT 446B (3)
4.	Hydraulic Excavator	CAT 311B (2)
5.	Hydraulic Excavator	CAT 375 (1)
6.	Off-Highway Hauler	CAT 777D (5)

All the fault categories identified and previously listed in Table 6.4 were utilised in synthesising the data set for the investigation. Each fault was allocated a weighting based on the frequencies of fault occurrence observed on the 330 Samsung, Volvo and Caterpillar plant items studied (refer to Table 6.1 for details).

40 fault categories were defined as listed in Table 6.6. Categories 1 to 38 were based on observations of fault type occurrence frequencies. Category 39 accounts for 'breakdown' events due to general service and routine maintenance, while category 40 refers to every other fault type. Table 6.6 shows the final fault categorisation and the weights in percentage terms associated with all the categories.

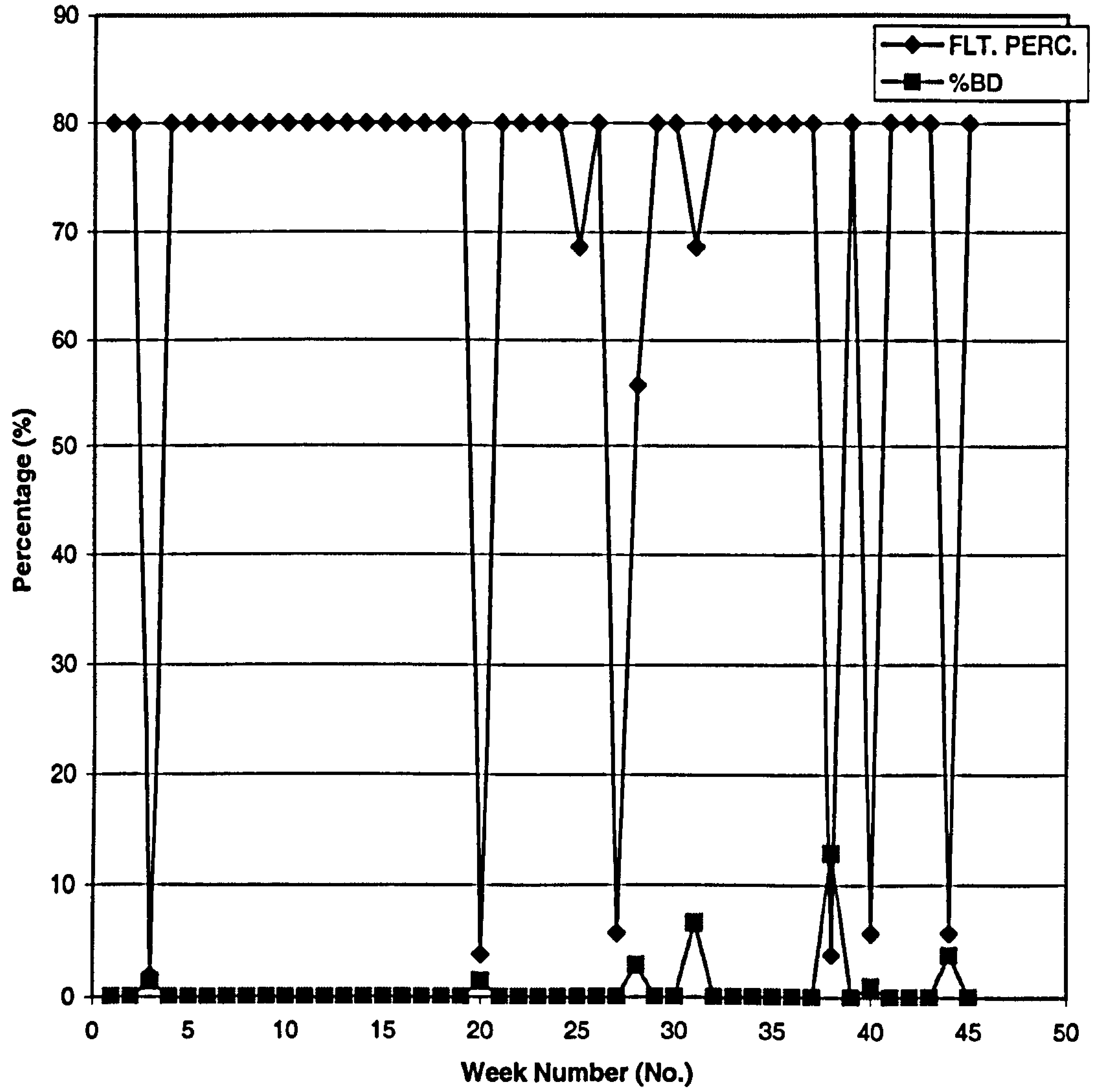
During the analysis of the 6 plant items (given in Table 6.5), each weekly observation in which a breakdown event was recorded was allocated an associated fault category and weighting in line with Table 6.6. Other weeks in which no breakdown occurred were weighted as a percentage of 'no-fault occurrences'. These were computed based on the weights of all faults recorded over the study period in reference. The values ranged between 70 and 80 percent in all cases. Breakdown percentages were computed for each breakdown observation as the percentage of breakdown time in one week to the total plant available time in that week. So for a plant breakdown time of 5 hours out of a total plant available time of 50 hours, the breakdown percentage = 5/50 X 100 = 10 percent. Therefore, having allocated fault percentage weights and breakdown percentages for the six plant items, the influence of specific faults on breakdown was then investigated through a quantitative analysis of their frequency. Figures 6.2 to 6.7 show all the analysis results.

Table 6.6: Fault Categorisation and Weights

Category	Fault	Weighting (%)
1.	Heater ACU valve/ matrix leaking	7.17
2.	Quick hitch pipes/ leak	5.39
3.	Electrical faults	5.15
4.	Hydraulic leak	5.07
5.	Hydraulic pressures reset, adjust or check	4.03
6.	Windscreen wiper linkage	3.62
7.	Hose rupture valve	3.54
8.	ACU/ heater general faults	2.9
9.	Quick hitch electrics	2.9
10.	Throttle linkage & mode switch	2.74
11.	Hammer pipes or clamps	2.74
12.	Tracks wearing, track tension	2.74
13.	Paint spray or sign writing	2.66
14.	Hydraulic pipe mod or repair	2.58
15.	Engine speed sensor	2.25
16.	Radio and aerial	2.25
17.	Starter motor	2.09
18.	Electronic control unit	2.01
19.	Bucket pins, shims & links	2.01
20.	Stepping motor	1.93
21.	Centre passage oil leak	1.93
22.	Boom mod	1.85
23.	Hydraulic noise or vibration	1.85
24.	Main valve bank hydraulic leak or fault	1.77
25.	Slew ring oil leak	1.77
26.	Bottom track roller	1.69
27.	Boom base check	1.69
28.	Fuel filling pump	1.61
29.	Quick hitch general faults	1.61
30.	Erratic revs/ transmission	1.61
31.	Vandal guards	1.61
32.	Travel motor/ puncture	1.53
33.	Windscreen or window	1.53
34.	Coolant leak	1.53
35.	PDI/ steering ram	1.53
36.	Stop solenoid or control	1.45
37.	Slew ring general faults	1.37
38.	Battery and associated parts	1.29
39.	General service	2.42
40.	Other faults	2.42

The results revealed that the specific nature of the faults had significant effects on plant breakdown time as opposed to the frequency with which they occurred. Although some of the faults were weighted approximately with the same magnitude, effects on breakdown time varied from fault category to fault category. This observation also further helped in the definition of fault occurrence as an independent variable for plant breakdown prediction. For example, two different types of faults were observed in week numbers 26 and 27 for the CAT 994D (6) wheel loader (Figure 6.3). These were throttle and hammer pipe related faults respectively, which had equal fault percentage (FLT. PERC.) value of 2.7 per cent. However, the resultant breakdown percentage times were 8 per cent for the throttle fault and 13 per cent for the hammer fault respectively.

Figure 6.2: Fault and Breakdown Percentages for CAT 908 (6) Wheel Loader

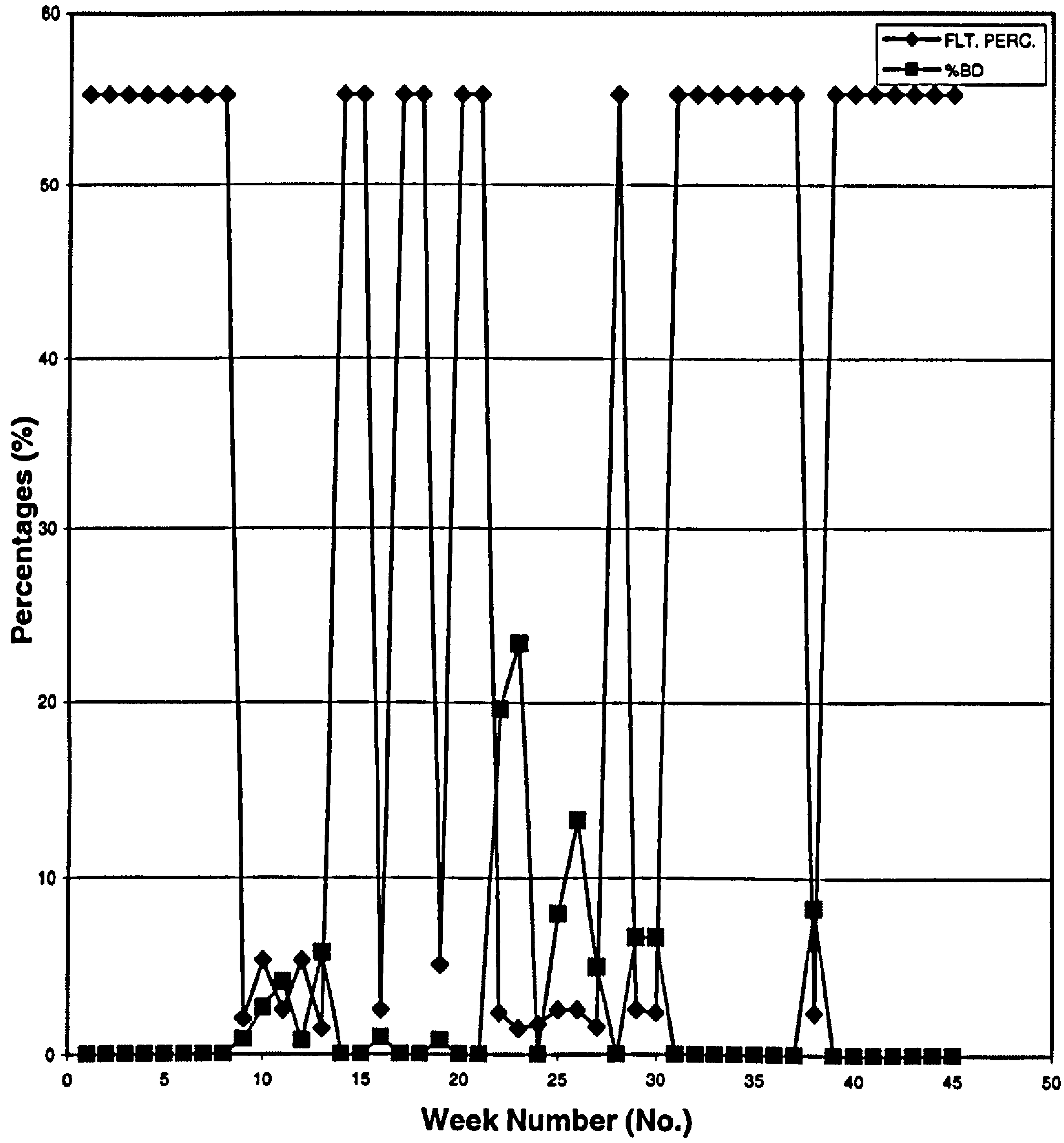


KEY:

FLT. PERC = Fault Percentage

%BD = Percentage Breakdown time

Figure 6.3: Fault and Breakdown Percentages for CAT 994D(6) Wheel Loader

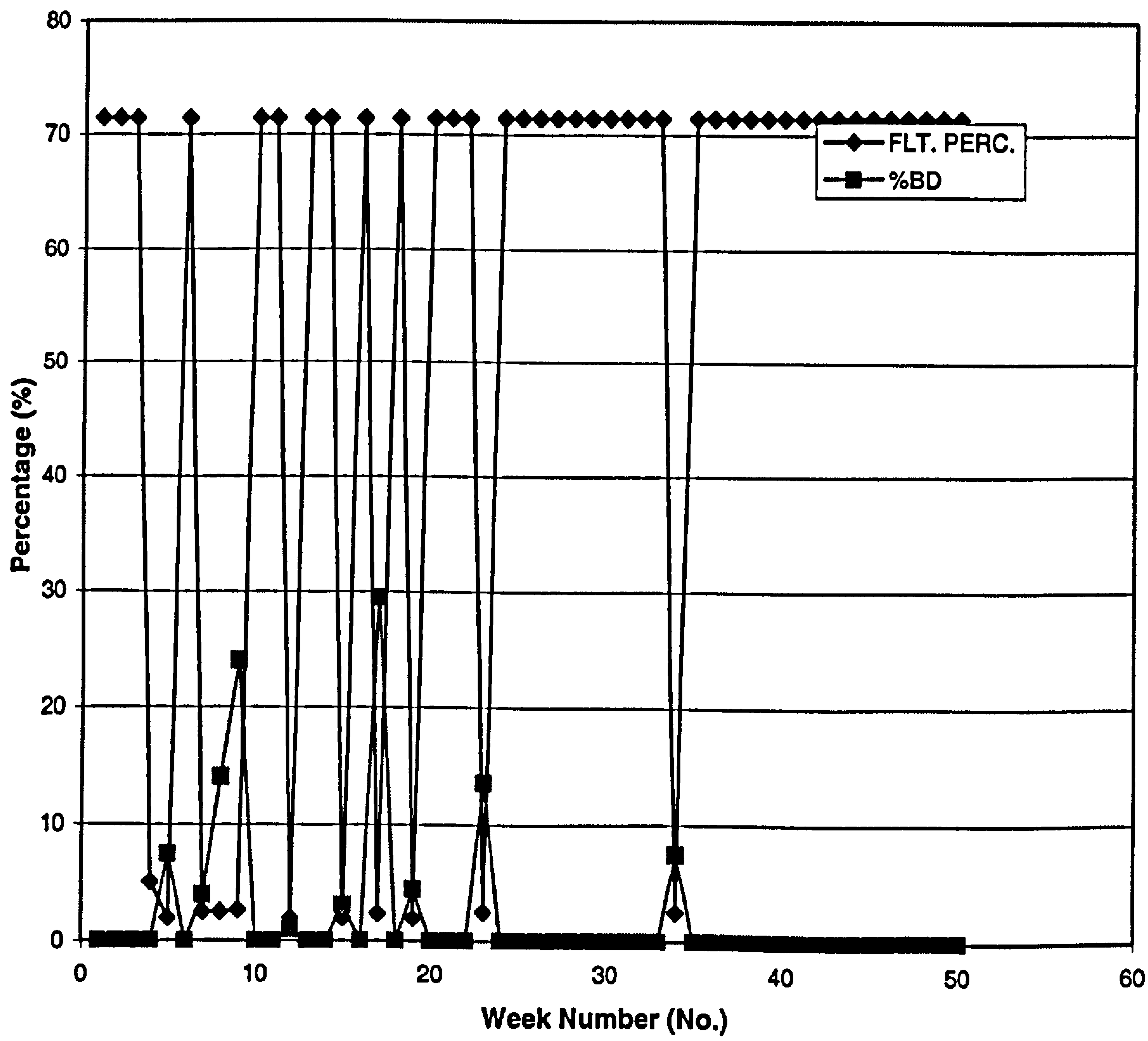


KEY:

FLT. PERC = Fault Percentage

%BD = Percentage Breakdown time

Figure 6.4: Fault and Breakdown Percentages CAT 446B (3)

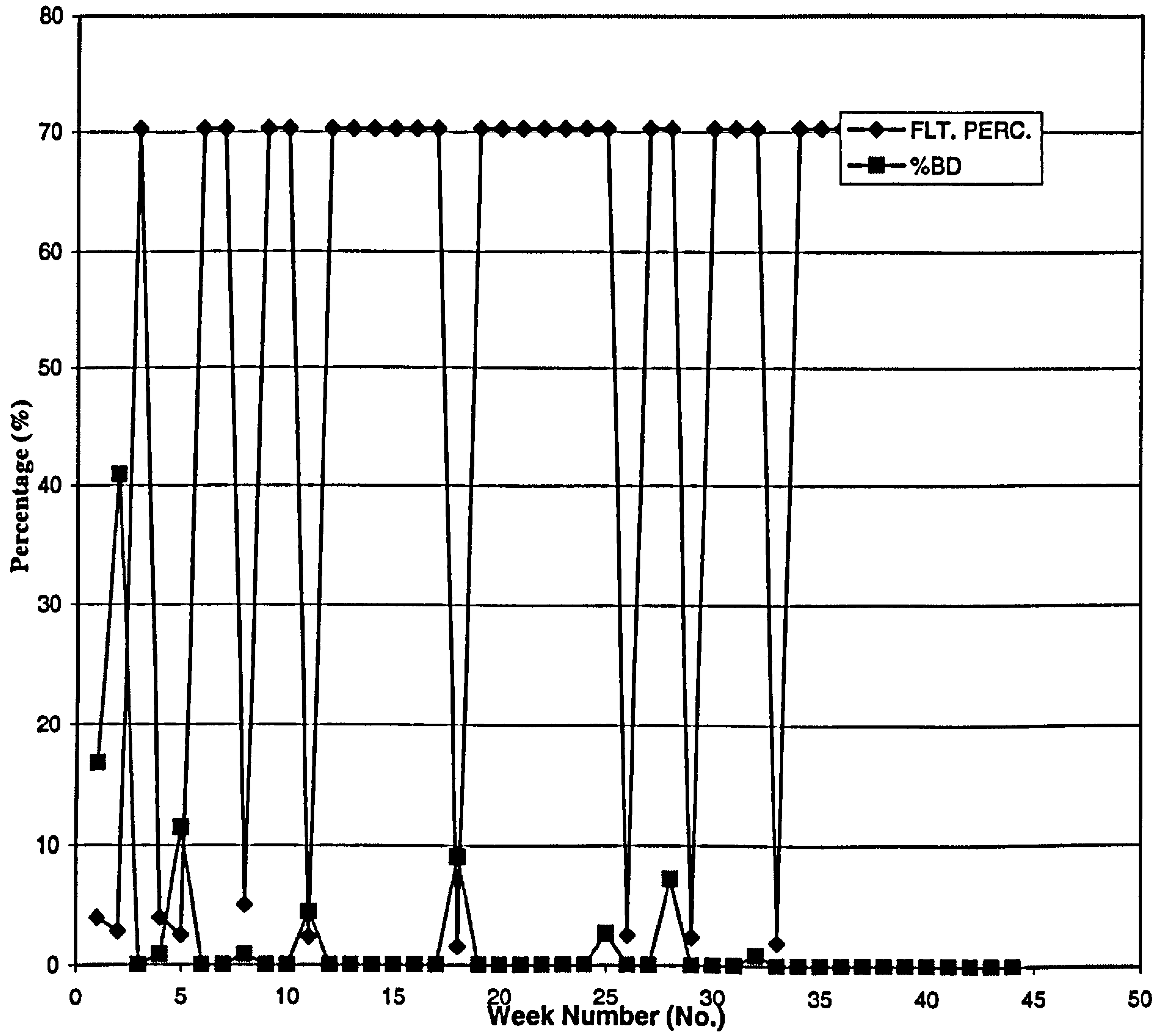


KEY:

FLT. PERC = Fault Percentage

%BD = Percentage Breakdown time

Figure 6.5: Fault and Breakdown Percentage CAT311B (2)

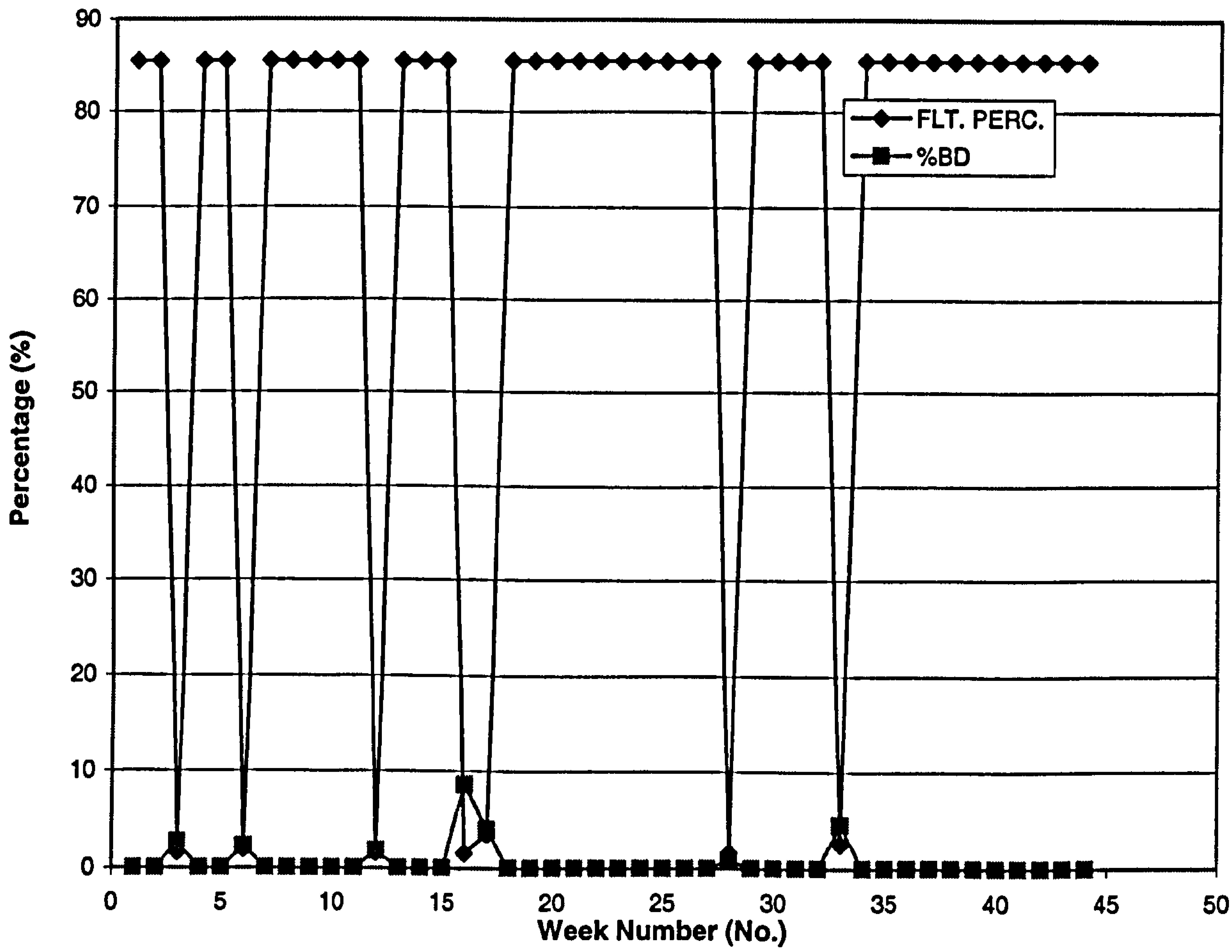


KEY:

FLT. PERC = Fault Percentage

%BD = Percentage Breakdown time

Figure 6.6: Fault and Breakdown Percentages for CAT 375 (1)

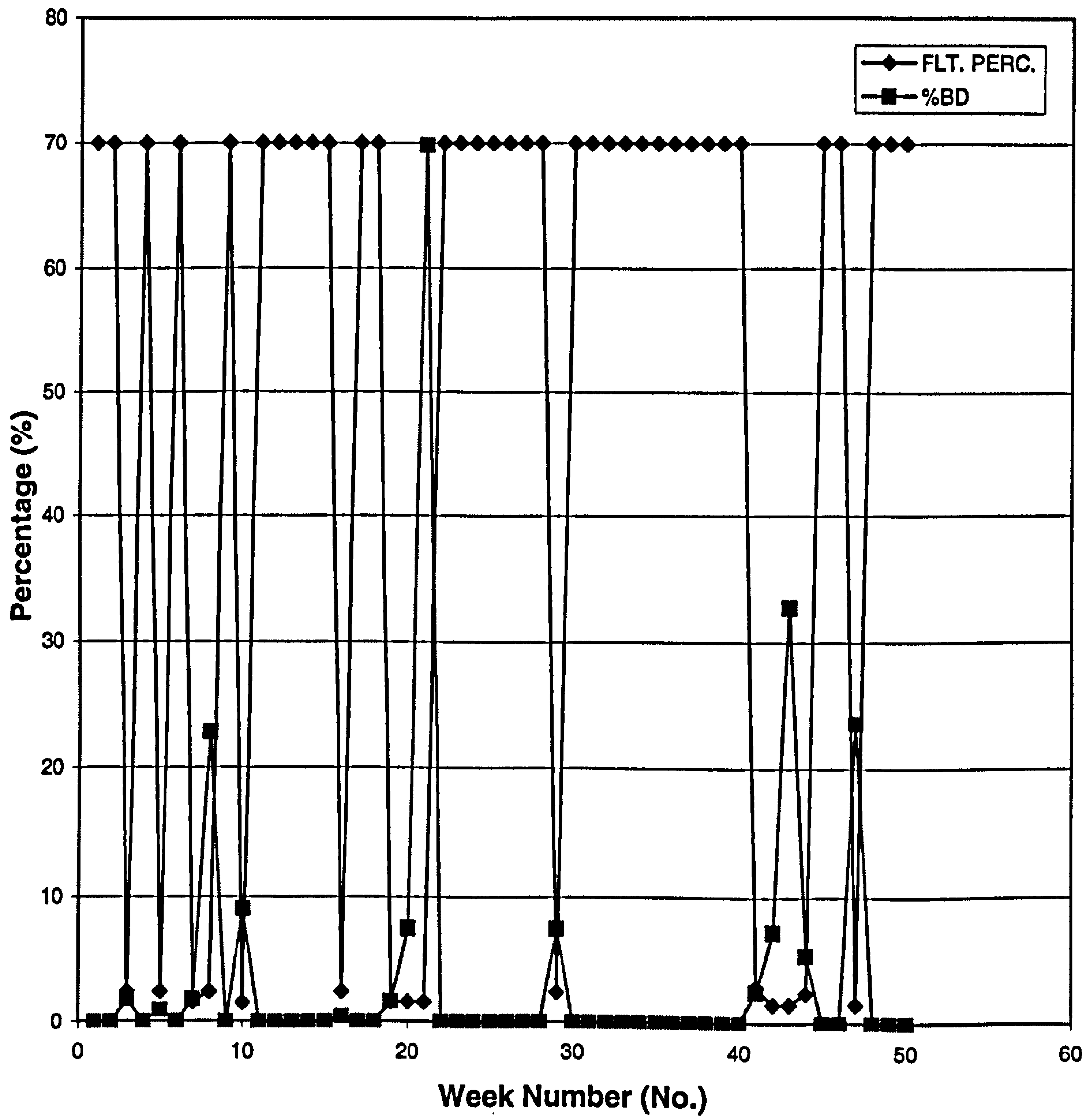


KEY:

FLT. PERC = Fault Percentage

%BD = Percentage Breakdown time

Figure 6.7: Fault and Breakdown Percentages CAT 777D (5)



KEY:

FLT. PERC = Fault Percentage

%BD = Percentage Breakdown time

PLANT PARAMETER MODELLING: A SYNOPSIS OF RECENT STUDIES

Several contributions have been made to determine the best means of modelling off-highway plant parameters (Gerold, 1997; Edwards, 1999; Haidar *et al*, 1999; Edwards *et al* 2000; Edwards and Holt, 2001; Edwards and Yisa, 2001). Generally, these studies were aimed at utilising plant history records for modelling some plant performance parameters such as: maintenance scheduling (Gerold, 1997), equipment selection optimisation (Haidar *et al*, 1999); maintenance costs (Edwards, 1999), breakdown magnitude assessments (Edwards *et al* 2000), utilisation, standing time and cumulative breakdown time (Edwards and Holt, 2001) and plant downtime modelling (Edwards and Yisa, 2001). The models derived could either predict future values or model the magnitudes of the parameters. Two most prominent parameters in which efforts have significantly concentrated are plant maintenance costs prediction (Edwards, 1999) and plant breakdown magnitude assessment (Edwards and Yisa, 2001).

Plant Maintenance Cost Prediction

In a recently concluded PhD research (Edwards, 1999), a wide range of plant history data were collated, analysed and modelled using various techniques. These included:

i) Bivariate Regression (BR) analysis for paired data
ii) Multiple Regression (MR) analysis
iii) Artificial Neural Networks (ANN) using the multi-layer perceptron technique and

iv) Exploratory 'time series' analysis (to determine why 'time' was not identified as a relevant predictor variable in the prediction of maintenance costs).

Generally, the analyses were conducted to facilitate the prediction of the total average hourly maintenance cost of tracked hydraulic excavators operating in the UK open cast mining industry. Results showed, in respect of the various techniques adopted, that:

i) multiple linear regression analyses proved excellent for predicting the maintenance cost for the equipment;

ii) based on the outcome of a performance analysis carried out on the MR model, it could be concluded that the model's predictive power is good; but that

iii) the ANN is the most robust and will be of use to construction plant managers based on the performance analysis and model validation tests. The research further recommended the application of other methods such as time series analysis to model plant history data.

Transformation of input data has also been observed to improve the predictive capabilities of models (You and Chandra, 1998; Edwards, 1999; Shi, 2000). The primary purpose of data transformation is to modify the distribution of input variables so that they can better match outputs (Shi, 2000). The performance of a neural network, for instance, is often improved through data transformations (Famili *et al*, 1996). It was also demonstrated that, in addition to the traditional techniques of; linear transformation, statistical standardisation and mathematical functions, it is possible to transform data using cumulative distribution functions with a process known as distribution transformation (Shi, 2000).

Plant Breakdown Modelling

When compared to plant maintenance cost modelling, plant breakdown is a 'less predictable' parameter. Generally, prolonged project durations and increased project costs are symptomatic of machine breakdown (Hendrickson, 2000). Past research has suggested the possibility of modelling this phenomenon as a way of curbing its impact upon plant productivity and maintenance management (Lundegard, 1998; Edwards, 1999; Edwards and Yisa, 2001). Edwards and Holt (2001) revealed that effective documentation of plant breakdown has assisted management monitor breakdown occurrence and its probable impact upon project productivity. Other researchers have modelled the magnitude of plant breakdown using stochastic random numbers (Edwards and Yisa, 2001). However, there remains a need to develop a tool that can accurately predict the incidence of plant breakdown as a function of total plant hours and faults incidence. Such a tool would assist plant managers in the design and development of contingency plans that could forestall the impact of plant breakdowns upon project progress and thus, success.

This study therefore focussed on developing plant breakdown prediction models in order to contribute to research efforts and enhance off highway plant information management.

SELECTION OF THE MOST APPROPRIATE MODELLING TECHNIQUE

As already established in chapter three, the development of a MBMS can be based on the assemblage of models developed from analysis of historical data (Guoha, 2001).

However, the abilities to invoke, run, change, combine and inspect models are key elements of intelligent systems (Berka, 1997).

Several options exist as modelling techniques upon which the development of INTELLIPLANT's MBMS could be based. The most relevant of these were reviewed and their capabilities were assessed in line with the objective of INTELLIPLANT. The reviewed techniques include: neural computing (artificial neural networks – ANN), genetic algorithms (GA), fuzzy logic and time series analysis. This review considered the principle behind each technique and its applicability to plant breakdown prediction modeling. Also considered is the ease of establishing models from each technique within the proposed MBMS and the integration of such MBMS with the RDBMS.

Artificial Neural Networks

This approach attempts to mimic the manner in which the human brain works (Picton, 1994). It is one of several approaches to machine learning (Goldberg, 1989). An ANN learns from trends in historical data, patterns or even pictures (Picton, 1994; Gurney, 1997). The most widely used neural networks are fully connected and feed forward with a single hidden layer (Patterson, 1995). Hence three layers are defined as: input, hidden and output (Weiss and Indurkhya, 1998). Every node in a layer is connected to every node in the layer above it (Saitta, 1996). Starting with linear solution of zero hidden units, a net can have a variable number of hidden units (multi-layer) (Bishop, 1996; Luger and Stubblefield, 1998). The inputs are the feature value of a case and these are combined in equations 6.1 and 6.2 to compute and produce outputs (Swingler, 1996; Weiss and Indurkhya, 1998).

$$net_j = \sum_{i=1}^{N} W_{ij} I_i + \theta_j \tag{6.1}$$

$$O_j = \frac{1}{1 + e^{-net_j}} \tag{6.2}$$

Where (for a two-part computation):

$j =$ Node number;

$N =$ Input nodes numbered from $i = 1$ to N;

$W_{ij} =$ Weight of the link between i and j;

$I_j =$ Input from node i;

$\theta_j =$ Constant value associated with j; and

$O_j =$ Node Output.

The usual process of learning involves three tasks (Turban and Aronson, 2001). These are: compare outputs, compare outputs with desired targets; and adjust weights and repeat the process (ibid). Therefore, the learning process starts by setting weights, either by some rules or randomly (Edwards, 1999). The difference between the actual output (Y) and the desired output (Z) for a given set of input is delta, an error function (Wang, 1994). The objective is to ensure local and universal minima in error hyperspace, i.e. the delta (or to reduce it to zero).

The benefits of neural network technology include its capabilities in pattern recognition, learning, classification, generalization and abstraction and their interpretation of incomplete and noisy outputs (Saitta, 1996). Also ANNs have the ability to tackle new kinds of problems, are robust, have a fast processing speed and are flexible and easy to maintain. Neural networks can be applied where data are: multi-variate, with a high degree of interdependence among attributes, noisy or incomplete, or many hypotheses are to be pursued in parallel and high computational rates are required.

However, ANNs do not perform so well at tasks that are difficult to do by humans (Turban and Aronson, 2001). The method has inherent complexity and the 'black box' nature of computation can be difficult to replicate in other systems (Picton, 1994). Finally, neural computing requires a large amount of training data (Bishop, 1996). These drawbacks therefore greatly affect the consideration of ANN's as a suitable modelling technique for off-highway plant breakdown prediction.

Genetic Algorithms

Genetic algorithms are systems that demonstrate self-organisation and adaptation on the sole basis of exposure to the environment (Goldberg, 1989). GAs were invented by John Holland in the 1960's based on Darwin's evolution theory (Mitchell, 2001). They are similar to biological organisms (Adeli and Hung, 1995). Holland's GA is a method for moving from one population of "chromosomes" (e.g. strings of one and zeros, or "bits") to a new population by a "natural selection" together with the genetics-inspired operators of cross-over, mutation and inversion (Karr, 1995; Mitchell, 2001). GAs can be viewed as a type of machine learning for automatically solving complex problems. GAs provide a set of efficient, domain-independent search heuristics for a broad spectrum of applications (McCluskey and Annand, 1999). A GA receives information that enables it to reject inferior solutions good ones. Also, genetic algorithms are suitable for parallel processing. Three primary operators are used by GAs, these are: reproduction – a process of producing new generations of improved solutions; crossover – choosing a random position on the string and exchanging the segments either to the right or to the left of this point with another string partitioned similarly; and mutation – an arbitrary change in situation (Vagenas and Nuziale, 2001).

The application of GAs is mostly related to applications such as: driver scheduling in a public transportation system (Boden, 1987), job scheduling and assignment of destinations to sources (Karr, 1995), equipment reliability assessment (Vagenas and Nuziale, 2001),etc. Since the objective of the models to be developed for INTELLIPLANT is to predict plant breakdown, GA based models were, therefore, not consider a favourable option.

The combination of GA and ANN in a hybrid system was also investigated. This approach allows the coupling of a neural network with genetic algorithms to discover attribute weights (McCluskey and Anand, 1999). This method will however, require a four-step procedure. First, it will be necessary to determine the optimal weights for individual plant parameter attribute (either by utilisation of expert knowledge of data mining) (Kathman, 1993; Kerber *et al*, 1995). Second, there will be the need to apply the nearest neighbour algorithm incorporating enhanced distance metrics and applying the derived attribute weights to retrieve comparable historical breakdown data (McCluskey and Anand, 1999). This procedure is verified mathematically by computing the attribute significance, w_j:

$$w_j = \frac{s_j - \min\{s_k : 1 \le k \le n\}}{\max\{s_k : 1 \le k \le n\} - \min\{s_k : 1 \le k \le n\}} \tag{6.3}$$

Where: s_k is the significance of the k^{th} attribute; and n is the number of the attributes (e.g. plant breakdown, utilisation and standby times) in the data set.

Third, each 'comparable' must be weighed in relation to its comparability with the subject plant item. The objective of this step is to compute a comparable weight for the *ith* variable (*Compwt$_i$*). This is expressed as:

$$Compwt_i = 1 - \left(\frac{|OH|_i}{\sum_{n=1}^{i} |OH|_i} \right) \tag{6.4}$$

Where: OH_i is the algebraic difference of cumulative operating hours between the i^{th} plant item to the subject plant item.

Finally, a prediction of the dependent (plant breakdown percentage) variable (BDP_i) can then be made in accordance with equation 6.5.

$$BDP_{i+1} = \sum_{n=1}^{i} \frac{(Compwt_i . BDP_i)}{2} \tag{6.5}$$

Where: BDP_i is the breakdown percentage of the ith plant item.

Although, the hybrid technique appears a more reliable approach as opposed to the application of ANN and GA as stand alones, it was still not considered the most suitable for predicting plant breakdown. This is because the method is over-reliant on a meticulous input of the historical data set – a requirement that is not considered suitable for the off-highway plant sector (Oloke and Edwards, 2001). The hybrid system also requires a complicated assemblage of the ANN and GA algorithms for each simulation (Goldberg, 1989; Kathman, 1993; Karr, 1995).

Fuzzy Logic

Fuzzy logic deals with uncertainty (Foslein and Samad, 1995). The process simulates the process of human reasoning by allowing the computer to behave less precisely and logically than conventionally (Luger and Stubblefield, 1998). Fuzzy logic provides: flexibility, options, freedom of imagination, allowance for observation and shortens the system development time (Mitchell, 1995). When fuzzy logic techniques are added to GA and ANN, a domain of knowledge representation and inference technique often referred to as 'soft logic' or the 'soft programming' results (Bertino *et al*, 2001).

Tools based on fuzzy knowledge-extraction techniques are quite useful for in supporting clustering techniques (Klimasuakas, 1995). For example, partitioning customers of a given company with respect to their behaviour over payments (Bertino *et al*, 2001). The method could also enhance project risk assessment (Tah and Car, 2001) and the development of a knowledge base management system for maintenance cost assessment amongst others (Oloke and Edwards, 2002a). However, a major disadvantage of fuzzy logic is that it is difficult to apply considering human input limitations. The problems stem from linguistic vagueness to difficulties in supplying the definitions needed (Chen, 1996). The method was therefore not considered suitable for the development of a plant breakdown prediction MBMS.

Time Series Analysis

Time series analysis is a technique that facilitates the prediction of dependent variables from historical records (You and Chandra, 1998). Unlike the analyses of random samples of observations, that are particular to other statistical techniques, time series analysis is based on the assumption that successive values in the data series represent consecutive measurements taken at equally spaced time intervals (Chatfield, 1996).

There are two main goals of time series analysis, these are: i) to identify the nature of the trend of the sequence of observations; and ii) to forecast, that is, predict future values of the observed series (Anon, 1999). Both of these goals require that the pattern of observed time series data is identified and formally described. Once this is achieved, the pattern can be interpreted and integrated with other data and trends (Edwards et al, 2001).

Most time series patterns can be described in terms of four basic classes of components: cycle, irregularity, trend and seasonality. Cyclical patterns explain the effects of seasonal variations, while irregularity patterns expose points of the data that may be erroneous (Horton, 1997). The trend pattern on the other hand, represents a general systematic linear or (most often) non-linear component that changes over time and does not repeat, or at least, does not repeat within the given time range.

Seasonality, however, explains the series as it repeats itself in systematic intervals over time (Kendall and Ord, 1993; Horton, 1997). The time series approach was therefore selected for modelling plant breakdown time during this study. This is because the method can determine the effect of some 'outside event' that intervenes and consequently, changes the normal behaviour of a series before and after the occurrence of such an event (Chatfield, 1996). This attribute excoriates a particularly appealing aspect of the technique and illustrates its potential to model off-highway plant breakdown time. That is, breakdown time can thus be modelled as a function of the incidence of certain mechanical faults.

PLANT BREAKDOWN PREDICTION: A CONCEPTUAL TIME SERIES APPROACH

Several time series modelling options exist. These include trend extrapolation, smoothing, decomposition, filtering, regression etc. (Ruddock, 1995; Edwards *et al,* 2001). Two methods were initially considered for this analysis and are based on the non-seasonal nature of the data set (Kendall and Ord, 1993). These are: i) exponential smoothening; and ii) Autoregressive Integrated Moving Average (ARIMA) techniques. However, an initial trial of the exponential smoothening technique revealed that the smoothing coefficient (α) must be set to zero in order to obtain the best fit. This meant that the technique did not enable the use of information from the most recent observation in a series. Hence, the ARIMA technique was employed.

Autoregressive Integrated Moving Average (ARIMA) Technique

ARIMA models are flexible and widely used in time series analysis (Livney et al, 1993; Chatfield, 1996; Ray and Lewis, 1997). The technique combines as many as three types of processes: Auto Regression (AR); Integration (I); and Moving Averages (MA). These processes are all based on the concept of random disturbances and shocks (Ray and Lewis, 1997). The general ARIMA model, neglecting seasonality, is written as ARIMA (p, d, q); where p is the order of regression, d is the degree of differencing and q is the order of moving average involved (Edwards and Nicholas, 2001).

Several goodness-of-fit statistics are generated with the ARIMA solution. These include the coefficient of determination, R^2, which is used as an overall measure of the goodness-of-fit, and reflects the joint ability of all the explanatory variables to simultaneously describe the variations in the dependant variable (You and Chandra, 1998). Similarly the t-statistics are used as a measure of the appropriateness of the individual exploratory variables while the f-statistics measures the appropriateness of the inclusion or exclusion of a set of exploratory variables simultaneously (Horton, 1997).

Time series models in which the dependent variable is modelled as a function of the lagged (endogenous) dependent and exogenous independent variables can generally be expressed mathematically as:

$$Y_t = c + \phi_1 Y_{t-1} + \theta_1 X_{t-1} - e_t \tag{6.6}$$

Where: Yt = the dependent variable; c = a constant; et = the error term; Xt-1= the independent variable; ϕ_1 = the lagged dependent variable deduced autoregressive functions and θ_1 = the lagged independent variable deduced determined coefficients for the error terms (McDowall, *et al*, 1983).

For ARIMA models, the general model introduced by Box and Jenkins (1976) includes autoregressive as well as moving average parameters, and explicitly includes differencing in the formulation of the model (Chatfield, 1996).

Model Building Strategy

Box and Jenkins (1976) developed arguably the most popular strategy for building a time series model and defined three major stages of model building, namely: identification, estimation and diagnostic checking. Although Box and Jenkins originally demonstrated the usefulness of this strategy for model building, (specifically for ARIMA models) the general principles can be extended to all model building, for example, exponential smoothening, regression, intervention, seasonal regression and weighted least squares and spectral analysis (Lewis and Ray, 1997; You and Chandra, 1998; Anon, 1999; Edwards *et al*, 2001). Therefore, for this research, the approach developed by Box and Jenkins will be used.

SUMMARY

The descriptive analysis of the historical data conducted in this chapter has facilitated a clearer understanding of plant performance parameters. The assessments exposed the significant effect of plant breakdown time on general plant performance. Plant utilisation, maintenance and costs are drastically affected by the incidence of plant breakdown. From the frequency statistics, plant breakdown accounts for about 7 percent of total plant availability time (in the absence of plant standbys). This percentage (although would vary depending on plant age and working conditions) could reduce plant production rates significantly.

In the process of evolving a methodology for plant breakdown prediction, this descriptive analysis sought to explore the possible effects of including fault occurrence as an independent variable in proposed predictor models. This is because plant breakdown and associated maintenance costs are usually attributable to the incidence of fault(s) occurrence. However, the analysis of historical data revealed that the frequency of specific faults occurrences proved to be a better method of defining faults as opposed to faults definition due to the magnitude of maintenance costs. Further analysis of plant breakdown percentage time associated with fault percentage occurrence also revealed that the specific nature of faults had significant effects on plant breakdown time. This is in addition to the frequency with which the fault occurred.

Several contributions have been made to determine the best means of modelling off-highway plant parameters. Generally, these studies were aimed at utilising plant history records for modelling some plant performance parameters. However, this study is focussed on developing plant breakdown prediction models in order to contribute to research efforts and enhance off highway plant information management.

In selecting an appropriate modelling technique, the merits and demerits of available options were reviewed. The reviewed techniques include: neural computing (artificial neural networks), genetic algorithms (and hybrids of ANN and GA), fuzzy logic and time series analysis. The time series technique was selected because the method can determine the effect of 'outside events'. Furthermore, the method developed by Box and Jenkins was also proposed for building the proposed breakdown prediction model.

CHAPTER 7: INTELLIPLANT - Exploratory Time Series Analysis for Plant Break Down Prediction

INTRODUCTION

In this chapter, an exploratory analytical study was conducted on a sample set of the plant history data. Initially, the 6 CAT 908 wheel loaders were selected and the study utilised the time series approach to model plant breakdown duration prediction for the plant item. This was with a view to appraising the approach's suitability for the proposed model development. The study also served as a means of formulating a basis for applying the method to the historical data of other off-highway plant types. The objective of the procedure was to develop a concept for the model block of the MBMS. The functions of the MBMS are:

i) to improve plant maintenance management by providing practitioners with a useful predict tool for plant breakdown; and

ii) to reduce the likelihood of plant breakdown through the use of timely fixed-time-to maintenance, or at least, enable management to accurately predict downtimes in the event of breakdowns. Forewarned with such information, management can develop contingency plans to reduce the impact of breakdown upon project progress.

The exploratory analysis commenced with a comprehensive description and synthesis of the historical data. This was built upon the work carried out and presented in chapter 6. The emphasis in this chapter, however, was to examine the dataset on the

CAT 908 wheel loaders, which were selected for the exploratory analysis. During this stage, therefore, the comparison of plant availability, utilisation, breakdown and standing (standby) times was carried out for the selected plant items. In addition, the occurrence of faults as it pertained to each plant breakdown event was critically examined.

Model development then ensued using the SPSS Trends (version 10) software. The developed model was based on the analytical procedure defined by Box and Jenkins (1976). This entailed a rigorous evaluation of the selected independent variables namely the lagged: breakdown, fault occurrence, plant utilisation and plant standby times as percentages. All these were transformed as percentages of the hours of plant availability. The library of models developed will form the model base of the MBMS. The chapter then concluded with a discussion on the benefits of the exploratory model and a direction for applying the developed methodology to other plant types' historical data.

DATA DESCRIPTION AND SYNTHESIS

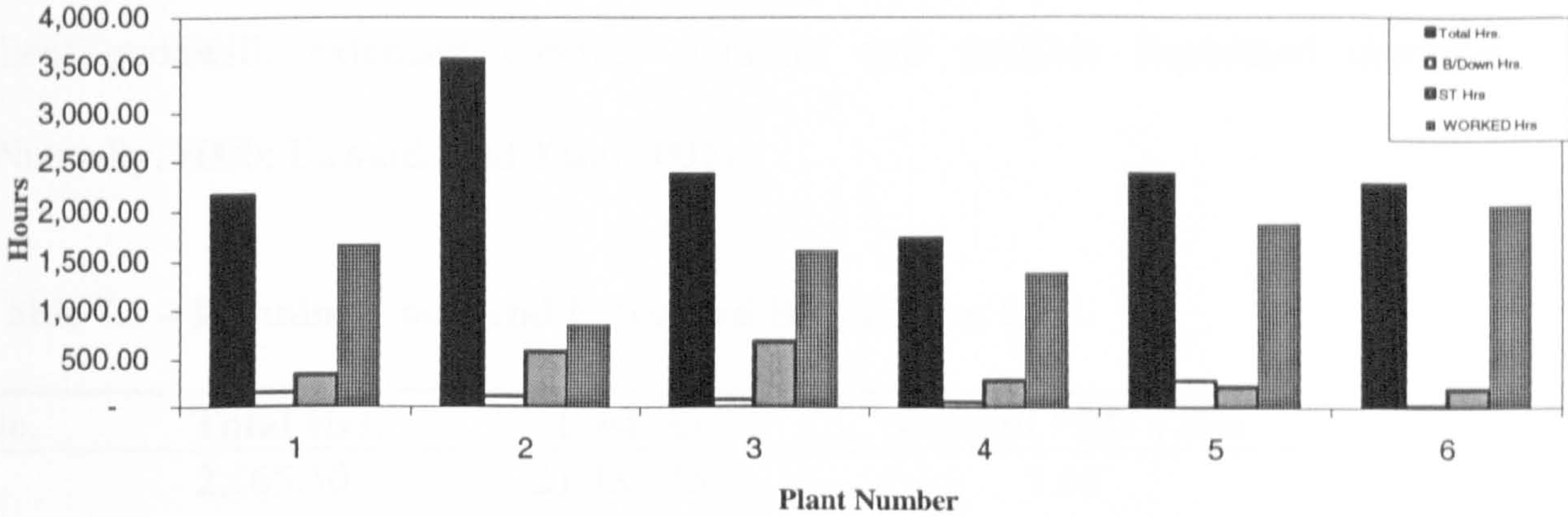
The historical data for the CAT 908 (1) to CAT 908 (6) wheel loaders consisted of daily observations of all the machines. Such observations include: plant utilisation, fault occurrence, standby and breakdown times. The plant items were of the same model and were working on a major aggregate/mineral production project. The total numbers of hours of observation (for all machines) was 14,467 and this was conducted over a 300-week period. For identification purposes during analyses, each machine was coded with an integer number ranging from one to six. Daily observations were aggregated into 50 weekly observations for each plant item.

Examination of each plant item's history file revealed that they were utilised interchangeably at three separate locations within the earthworks project over the 50-week period. Therefore, the operating conditions were broadly homogeneous. Unfortunately no records were made regards individual operator efficiency in operating and maintaining the plant (Cabahug *et al*, 2001). A follow-up telephone survey questioned individual plant managers and sought to determine the skill level of operators. It was revealed that each operator had a minimum of ten years experience and that they were *certificated to the Contractors Mechanical Plant Engineers national standard for competence.* Consequently, it is reasonable to assume that no major difference between individual operator performance exists.

Comparison of Plant Availability

A summary of plant activities during working hours is given in Figure 7.1. These activities include the total plant availability, breakdown, standing and worked times (in hours). Out of the 14,467 hours recorded for plant availability, plant item number two had the highest total availability hours of 3,562 hours, while plant item number four had the minimum with 1,730 hours. Other plant items (numbers one, three, five and six) had a total number of recorded hours between 2,165 and 2,378 hours. Reasons for this observed variance in availability are yet to be established definitively, although individual plant managers have proffered various explanations. The most convincing and probable is that plant item number four was a 'rogue' and that the company had experienced problems with this machine for some time; this being despite using the same maintenance regime.

Figure 7.1: Summary of Plant Hours



Comparison of Plant Utilisation, Breakdown and Standing Time

An evaluation of plant utilisation, breakdown and standing time was considered necessary because basic inventory details (for example, relating to the age of the plant and 'history' of utilisation, breakdowns and services prior to this project) were unavailable. The fundamental aim was to assess the recorded 'total breakdown' and 'standing' hours against the 'worked' time of each plant item. In turn this exercise enabled a fair insight into the characteristics of each plant item's performance. The hours worked varied between 861 hours for plant item number two to 2,053 hours worked for plant item number six, with a total of 9,460 hours for all the plants. Of the 14,467 hours recorded for total plant availability, the remaining time was made up of 703 hours for breakdown and 4,304 hours for standing time.

Generally, the total breakdown time amounted to an average of 4.94 per cent of the total period (hours) of plant availability. This amount of breakdown becomes significant when a comparison is made to the cost for running plant (Table 7.1). For example, the total cost for operating (hiring and maintaining) these plant items amounted to £103,085 over the 12-month period (UK sterling, 2000). Considering the percentage of breakdown time, an estimated £5,087.68 was incurred as downtime cost alone (Table 7.1); on top of this is the less tangible (but equally costly) cost of lost client goodwill, extended contract duration and possible liquidated damages (Nunnally, 2000; Edwards and Yisa, 2001).

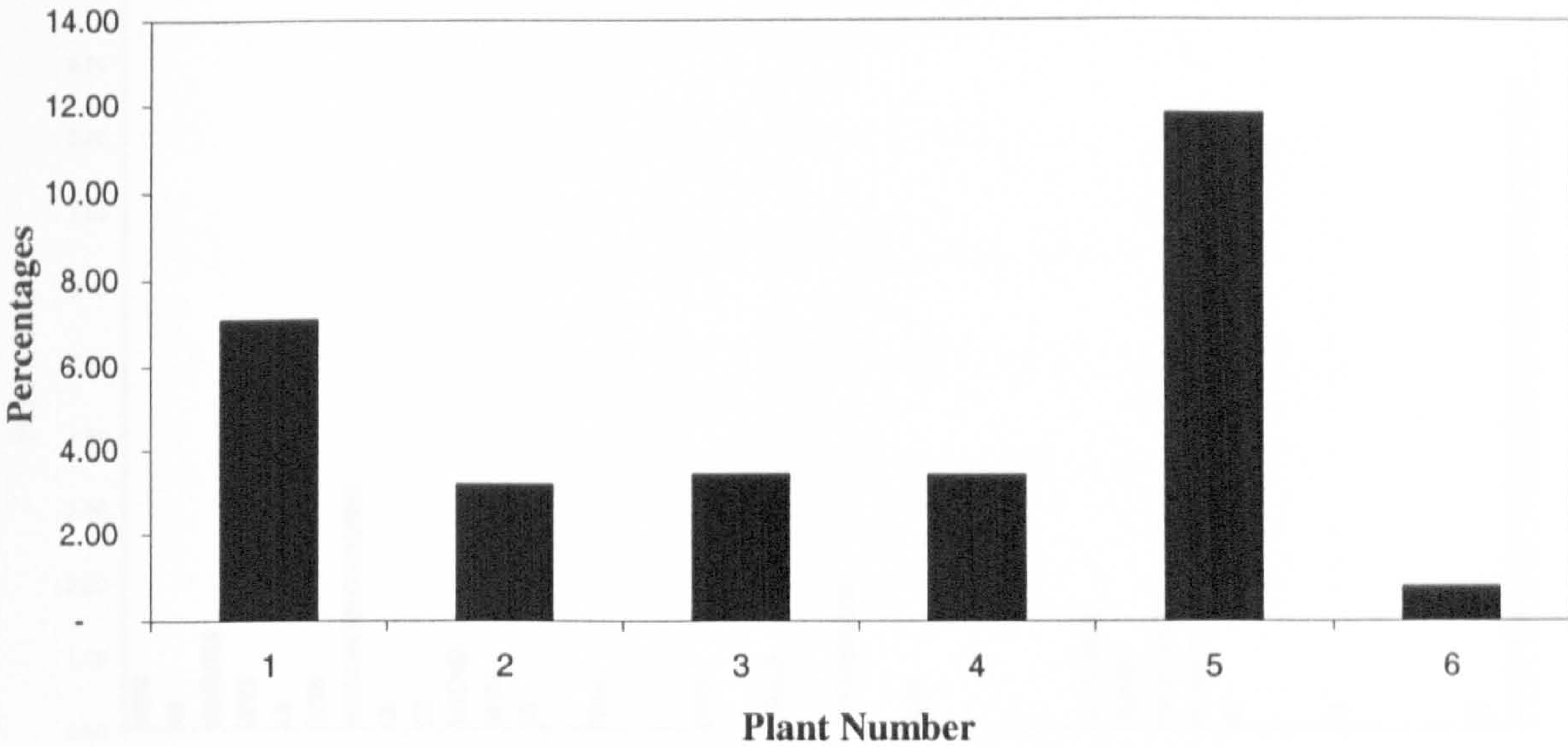
Table 7.1 – Running Costs and Estimated Breakdown Cost

No.	Total Hrs.	Cost (£)	Percent *BD Time
1	2,165.50	21,489.35	7.08
2	3,561.50	13,272.32	3.15
3	2,378.00	15,989.76	3.42
4	1,730.30	22,235.42	3.41
5	2,372.50	22,842.70	11.79
6	2,259.50	7,256.27	0.77
Sum	14,467.30	103,085.82	
	Average	Percentage *BD Time	4.94
	Average	*BD Cost (£)	5,087.68

* BD = Break Down

In order to aid the analytical procedure for predicting the plant breakdown time, the observed breakdown, standby and utilisation data was recomputed as a percentage of total hours worked by each plant. Figure 7.2 shows the results of the plant breakdown percentage results. Plant number five had the greatest value of 11.79 per cent, which is high when compared to the average percentage of 4.94 per cent across the sample. However, plant number 5 may be older than the rest and thus, incur additional costs as a result of rebuild or major works or conversely, it could just be an outlier.

Figure 7.2- Percentage Breakdown Time

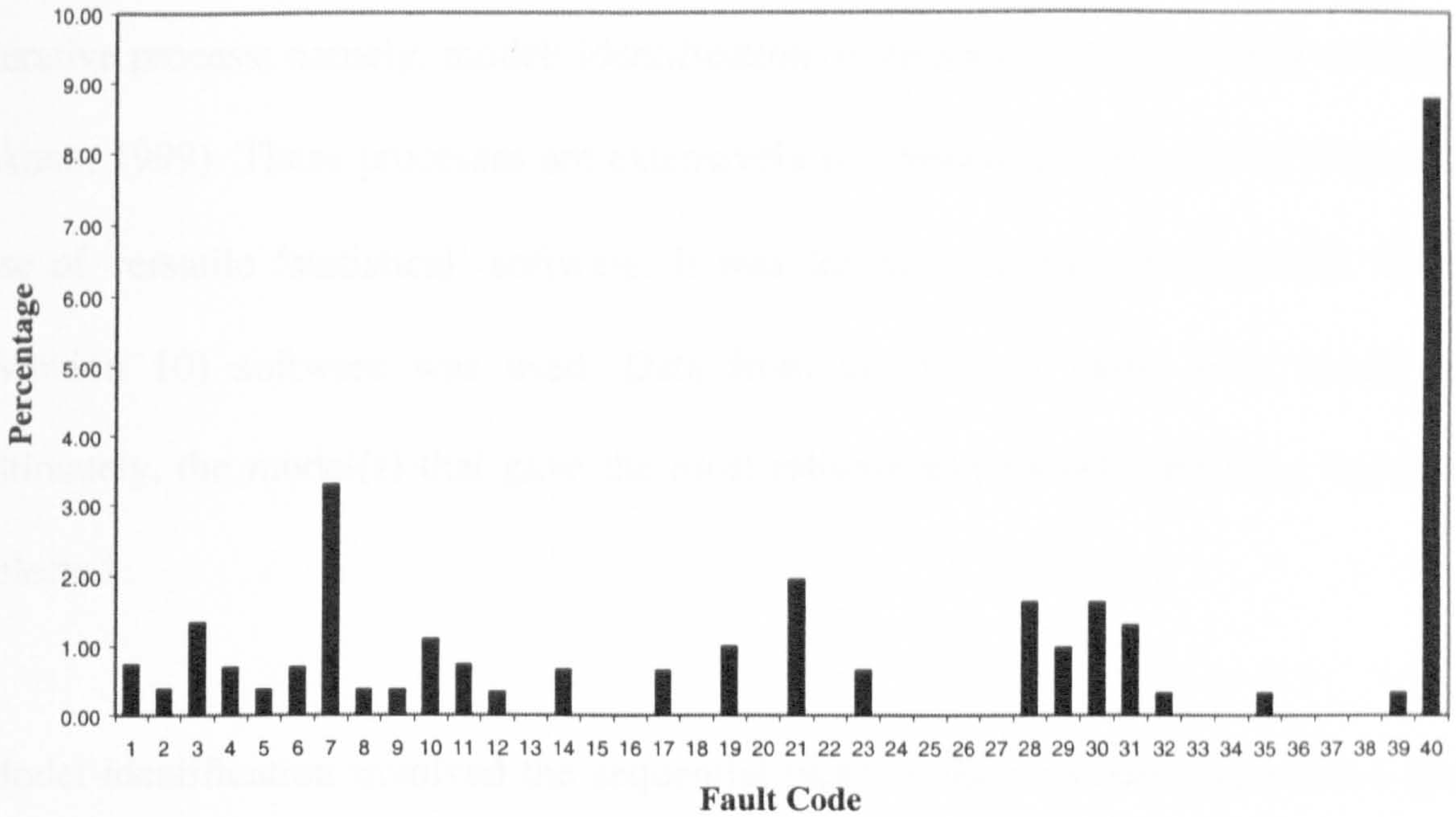


The Incidence of Fault Occurrence

The 40 different categories were evaluated in line with the breakdown incidence of the 6 CAT 908 wheel loaders investigated. These included 38 faults relating to major components such as hydraulics, undercarriage, electrical, fuels/oil, etc., and one code relating to the process of 'plant general service' (Table 6.6). The final code provided a separate categorisation for all other miscellaneous faults. Specifically, these specific groupings were derived from the results of a previous survey[1] that sought to develop a universal 'fault classification' coding system. A diagrammatic representation of the faults observed under this study together with their frequencies of occurrence is shown in Figure 7.3.

[1] Survey was conducted by an independent consultant from the UK Ministry of Defence investigating machine fault frequency and warranty cost reduction for a major UK plant manufacturer.

Figure 7.3 - Average Frequencies of Fault Occurrence



An examination of the frequencies of fault occurrence (Figure 7.3) shows that hose valve rupture fault (code no. seven) had the highest average percentage of occurrence of 3.28 per cent, while faults relating to tyre puncture, travel motor and the steering ram had the least average occurrence. Another important observation was that stoppages due to general service (code no. 39) were less than 0.40 per cent and were randomly distributed; an indication of a failure to adhere to a strict preventive maintenance programme. Finally, it was observed that the frequency of 'miscellaneous' faults (code no. 40) was more common than any other coded faults. This finding may illustrate the need to either increase the number of fault codes further and/or improve the fault reporting process. Within the off-highway plant sector, information management has been previously described as being notoriously poor and inadequate (Oloke *et al*, 2001).

ANALYTICAL PROCEDURE

The analytical procedure adopted for this investigation comprised of a four-stage iterative process; namely, model: identification; estimation; diagnosis; and validation (Anon, 1999). These processes are extensively mathematical and as such require the use of versatile 'statistical' software. It was for this reason that the SPSS Trends (Version 10) software was used. Data from all 6 plant items were tested and ultimately, the model(s) that gave the most reliable and robust predictive capability selected.

Model identification involved the sequential plots of the dependent variable – plant breakdown time percentage (BDPERC) for the determination of seasonality (periodic, repetitive and generally predictable patterns in the series) and stationarity (condition whereby variations on the data are invariant with regards to their displacement in time) (Horton, 1997). The Dickey-Fuller test (ibid) was also applied to confirm the stationarity of the series based on a chosen level of differencing (Kendall and Ord, 1993). Also, a critical assessment of the plots of the autocorrelation and partial autocorrelation factors for BDPERC was conducted to confirm the estimated parameters of the ARIMA model (You and Chandra, 1998). This procedure then led to the diagnosis of the selected model.

The model estimation and diagnosis procedure entailed a rigorous analysis of determining the most suitable selection and/or combination of independent variables for predicting BDPERC. Defined independent variables included: the lagged BDPERC; fault occurrence percentage (FLTPERC); plant standby time percentage (SBPERC); and utilisation time percentage (UTILPERC). It was also considered that other factors such as machine specifications, operator efficiency, work programme, working environment, type of industry and so forth could influence the incidence of plant breakdown (Edwards, 1999; Hendrickson 2000). However, some of these (for example, machine specifications and working environment) are constant or could remain relatively constant over long periods. Also, historical data captured as BDPERC could account for operator efficiency and the effectiveness of maintenance strategies, while SPBERC and UTILPERC data could individually or jointly account for the effects of changes in work programme, type of industry and so on. It could therefore be strongly argued that the independent variables selected are robust enough to account for the effects of these other factors. Four cases were therefore considered for the analyses. These were:

i. CASE I: Lagged BDPERC and FLTPERC as Independent Variables;
ii. CASE II: Lagged BDPERC, FLTPERC and SBPERC as Independent Variables;
iii. CASE III: Lagged BDPERC, FLTPERC and UTILPERC as Independent Variables; and
iv. CASE IV: Lagged BDPERC, FLTPERC, UTILPERC and SBPERC as Independent Variables.

Details of the results of the analyses considering the selected independent variables are discussed in the subsequent sections. The procedure was also used to model BDPERC for other plant types (using the best combination of the independent variables) as presented in the next chapter. The methods used to validate all models are similarly discussed in the next chapter.

The BDPERC Prediction Model Identification Process

Plots of the sequence charts for BDPERC against time (in weeks) revealed that the series were non-stationary and non-seasonal. However, the series indicated stationarity after the first differences were taken, as illustrated in Figures 7.4a and 7.4b for plant items number six. This result provides demonstrable evidence that a first-degree order of differencing may be suitable for the series. However, as a confirmatory procedure, the Dickey-Fuller test was applied on the series.

Figure 7.4a - Sequence Plot of Plant No.6 (Original Data)

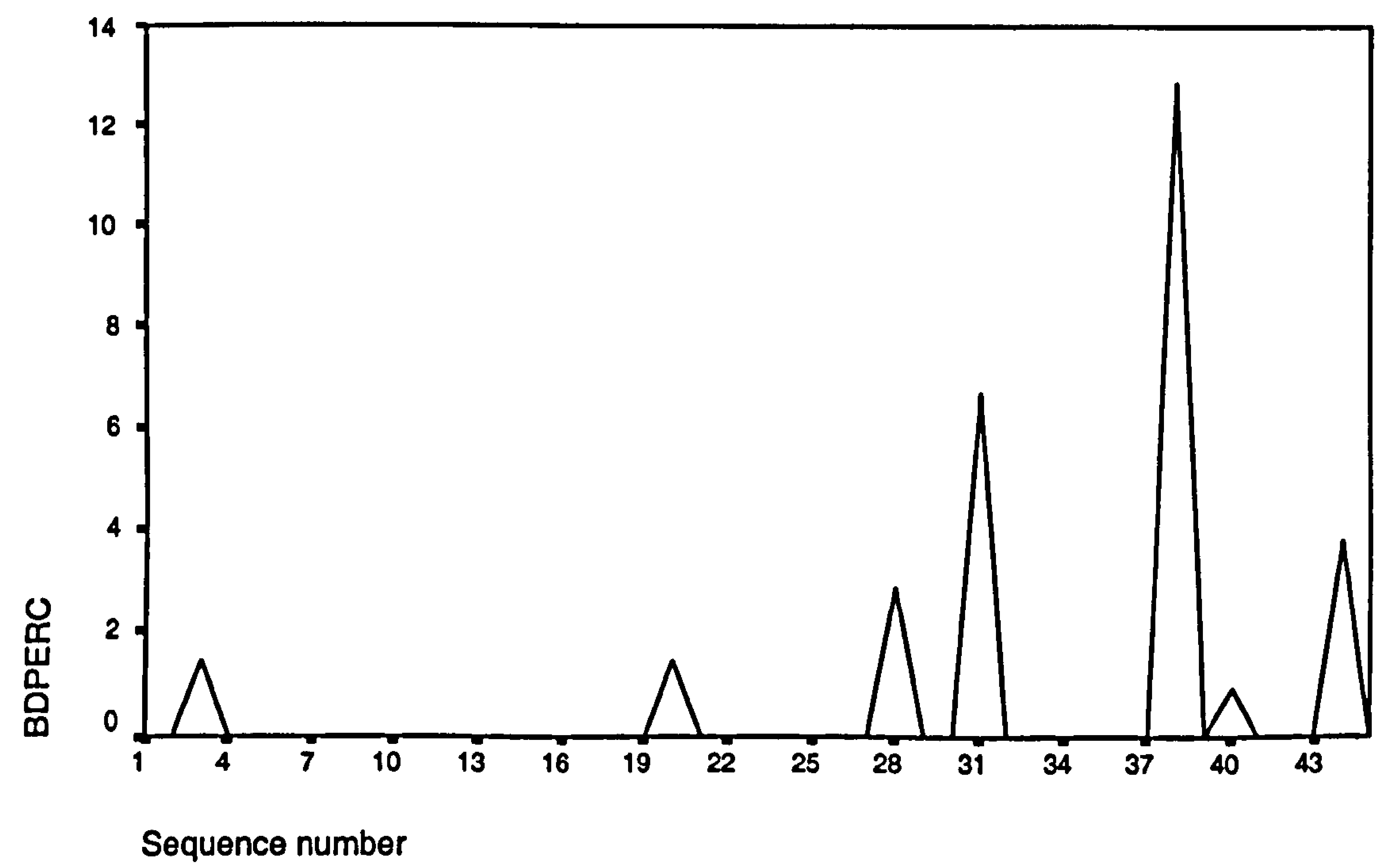
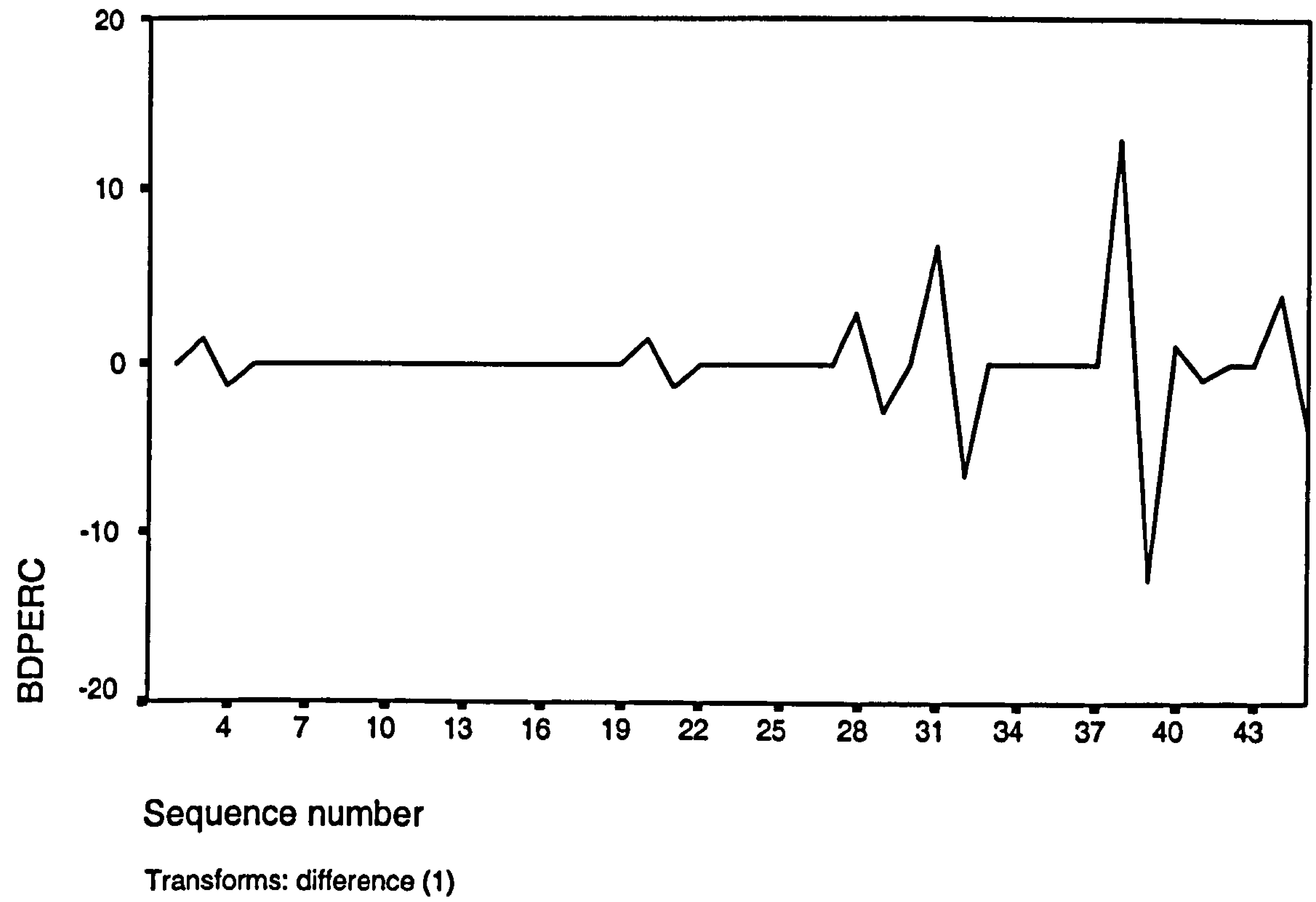


Figure 7.4b - Sequence Plot of Plant No.1 (Transformed)



Dickey-Fuller (DF) Test for Stationarity

To confirm the stationarity of the series using the DF test, the following regression was run:

$$y_t - y_{t-1} = \Delta y_t = \alpha_0 + \alpha_1 y_{t-1} + \varepsilon_t \qquad (7.1)$$

Where:

y_t = actual time series for BDPERC;

y_{t-1} = lagged time series for BDPERC;

Δy_t = differenced order for BDPERC;

α_0 and α_1 = roots of the regression function; and

ε_t = error term.

The aim was to test the hypothesis that $\alpha_1 = 0$. If the null hypothesis cannot be rejected, then the process can be inferred as having a unit root (Horton, 1997). Table 7.2 shows the critical values for the DF test (Kendall and Ord, 1993)

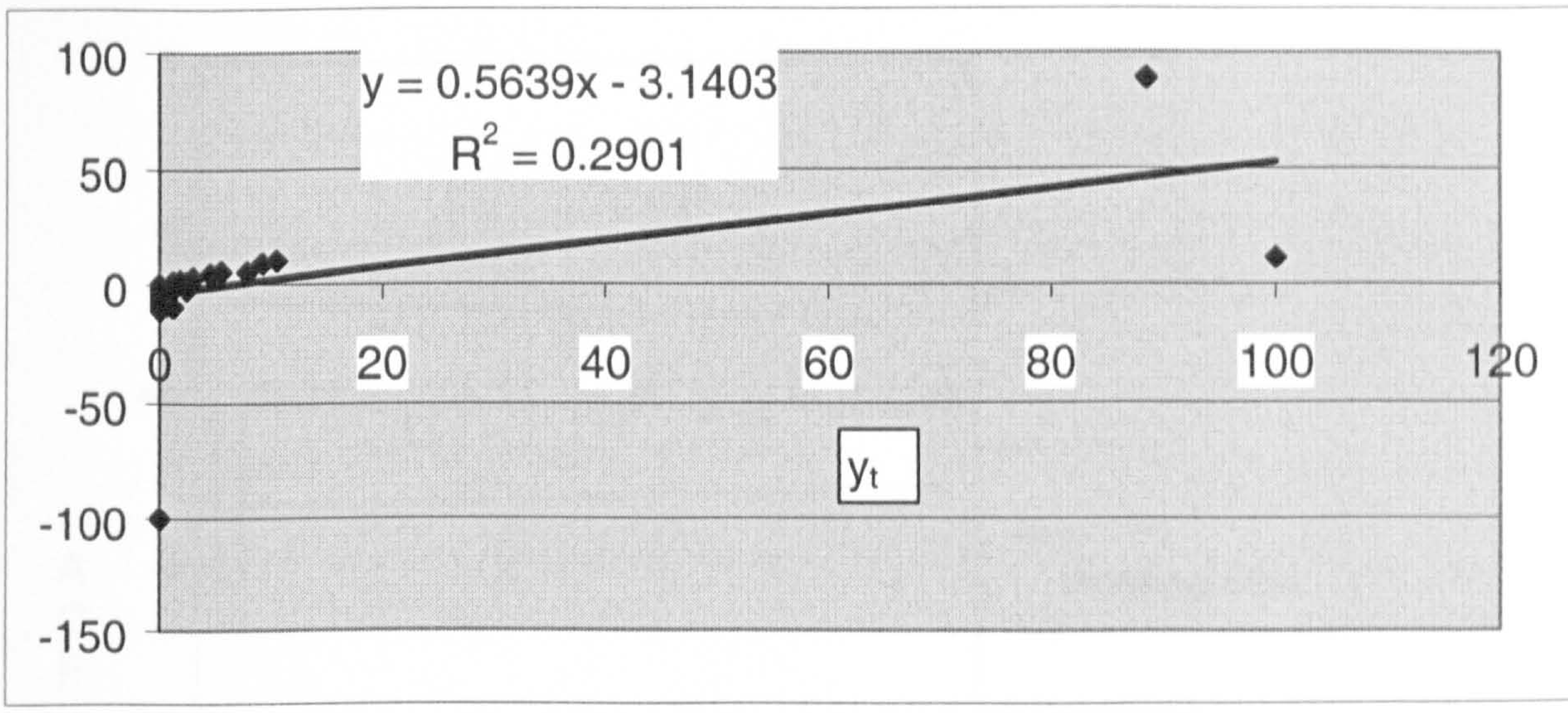
Table 7.2: Critical Values for the Dickey-Fuller Test

	Sample Size			
	25	50	100	∞
F Ratio (5%)	7.24	6.73	6.49	6.25
AR Model with Constant				
2%	-3.75	-3.58	-3.51	-3.43
5%	-3.33	-3.22	-3.17	-3.12
10%	-2.63	-2.63	-2.58	-2.57
AR Model with Constant and Time Trend				
2%	-4.38	-4.15	-4.04	-3.96
5%	-3.95	-3.80	-3.69	-3.66
10%	-3.24	-3.18	-3.15	-3.13

Regressing Δyt on the lagged value of yt gave an estimated slope coefficient $(\hat{\alpha}_1)$ of 0.5639 and a t-statistic of –3.14. From table 7.2, the 2% critical value for the 'AR model with constant and time trend' with 50 observations (in this case 42 - hence 50 is reasonable approximation) is –4.14, the 5% critical value is –3.80 and the 10% critical value is –3.18. Since -3.14 > - 3.18, the hypothesis that there is a unit root cannot be rejected. Based on this result, the series was therefore confirmed to be stationary by first-order differencing. The regression function is shown in figure 7.5.

Hence, the BDPERC prediction model was identified as an integrated and non-seasonal ARIMA model with d = 1 i.e. I (1). Having established a stationary series, the analysis then focused upon the identification of the autoregressive and moving average parameters (that is, p and q) that could adequately predict the series. Initial modelling utilised exponential smoothening and the ARIMA techniques.

Figure 7.5: Regression Results of Δyt on yt for CAT 908(6)



However, since analysis results indicated that the exponential smoothening technique was not reliable as it was not possible to use the most recent observations of the series for forecasts. Thus, the application of the ARIMA model was considered further for estimating forecasts of the BDPERC.

The plots of the autocorrelation function (ACF) (Figure 7.6a) and the partial autocorrelation function (PACF) (Figure 7.6b) were produced in order to determine the most suitable values for p and q for the ARIMA model. The autocorrelation function gives the autocorrelation values calculated at lags 1, 2 and so on, while the partial autocorrelation function gives the corresponding partial autocorrelations, for autocorrelations at intervening lags (Anon, 1999). Generally, the plots indicated that the ACF had exponentially declining values (with alternating positive and negative values) and a first significant spike in the first value of the PACF. This is a characteristic that signifies that the model is an AR (1) model (Kendal and Ord, 1993; Tong, 1990). An evaluation of the four cases proposed for the model estimation now follows.

Figure 7.6a - Plots of Autocorrelation for Plant No. 6

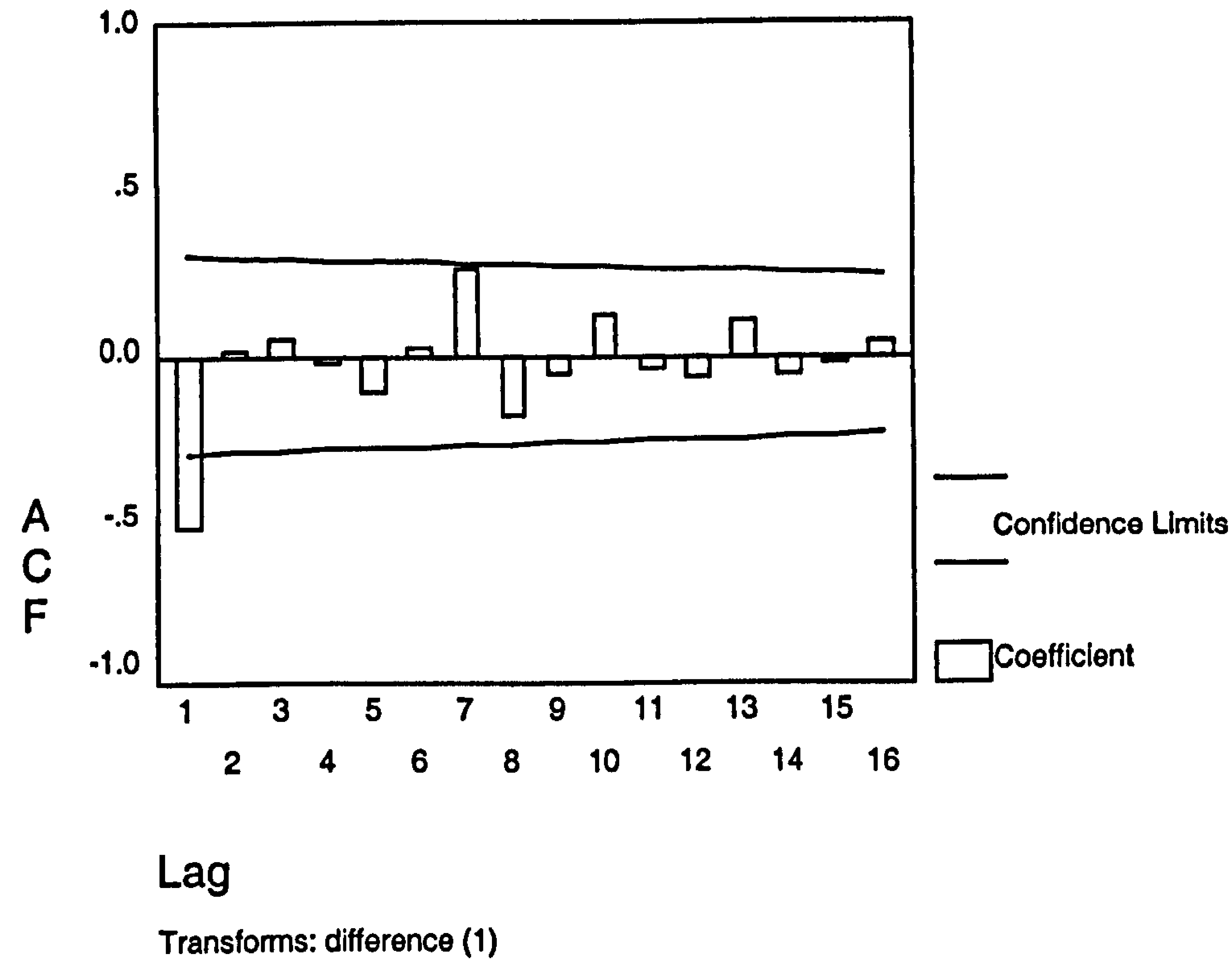
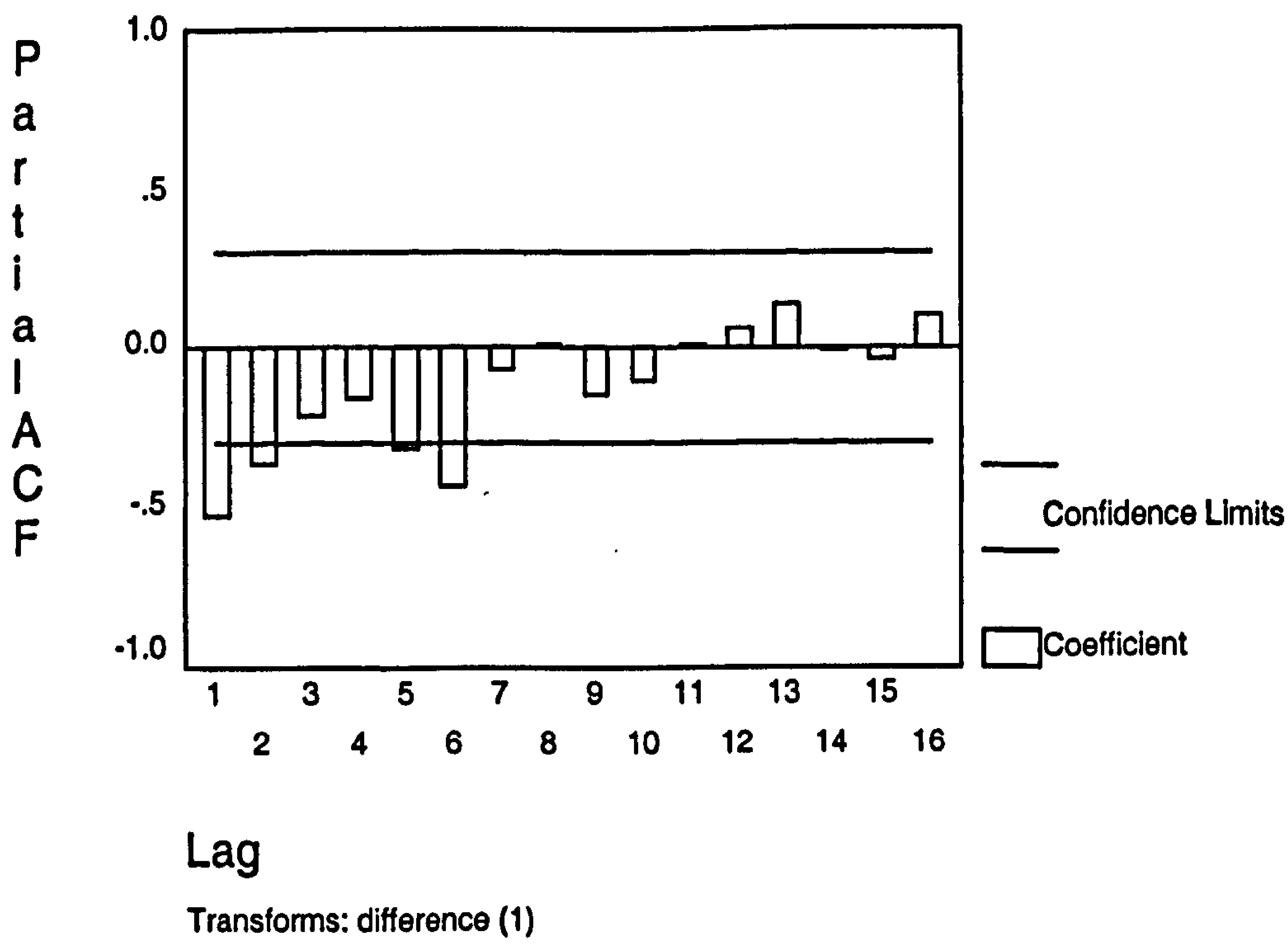


Figure 7.6b - Partial Autocorrelation for Plant No. 6



CASE I: Lagged BDPERC and FLTPERC as Independent Variables – (Model Estimation)

From the data set, the lagged BDPERC and FLTPERC were selected as the independent variables for case I. The tentatively identified ARIMA (1,1,0) model was then analysed using the SPSS software. Essentially, the analyses entailed a 'trial and error' process that observed the effect of the independent variables on the model's performance statistics and the fit curve of each of the series.

The dataset for plant item no. 6 gave the best results because it exhibited the least AIC and SBC. In addition, other regression outputs of the series such as the estimated standard errors, t-ratios and significance levels were the best values for the series. A diagrammatic plot of the fit curve for this series is shown in Figure 7.7, while Table 7.3 presents all the statistics. The plot illustrates the matching trends of the fit for BDPERC; falling reasonably well within the 95 per cent upper and lower confidence limits. Hence, this plant item was selected for further analysis of model diagnosis and demonstration.

Model Diagnosis and Demonstration – Case I

To ascertain the reliability of the selected model, it was important to check that it was compact and produced statistically independent residuals that contained only 'white noise' and no systematic components (McDowall et al, 1983; Chatfield, 1996). Residual plots for the selected model are shown for the ACF and PCF respectively (refer to Figures 7.8a and 7.8b). These reveal that the correlogram has no serial dependencies or white noise, because there are no 'observed' systematic trends in the plots. Generally, the ACF and PACF appear to be randomly distributed and only a few scattered correlations exceeded the 95 per cent confidence limits. Furthermore, the Box-Ljung statistic for the ACF function was not statistically significant at any lag; the R2 value was 0.290 with a standard error estimate of 2.502.

Figure 7.7 - Fit Curve Showing 95 per cent Upper and Lower Confidence Limits

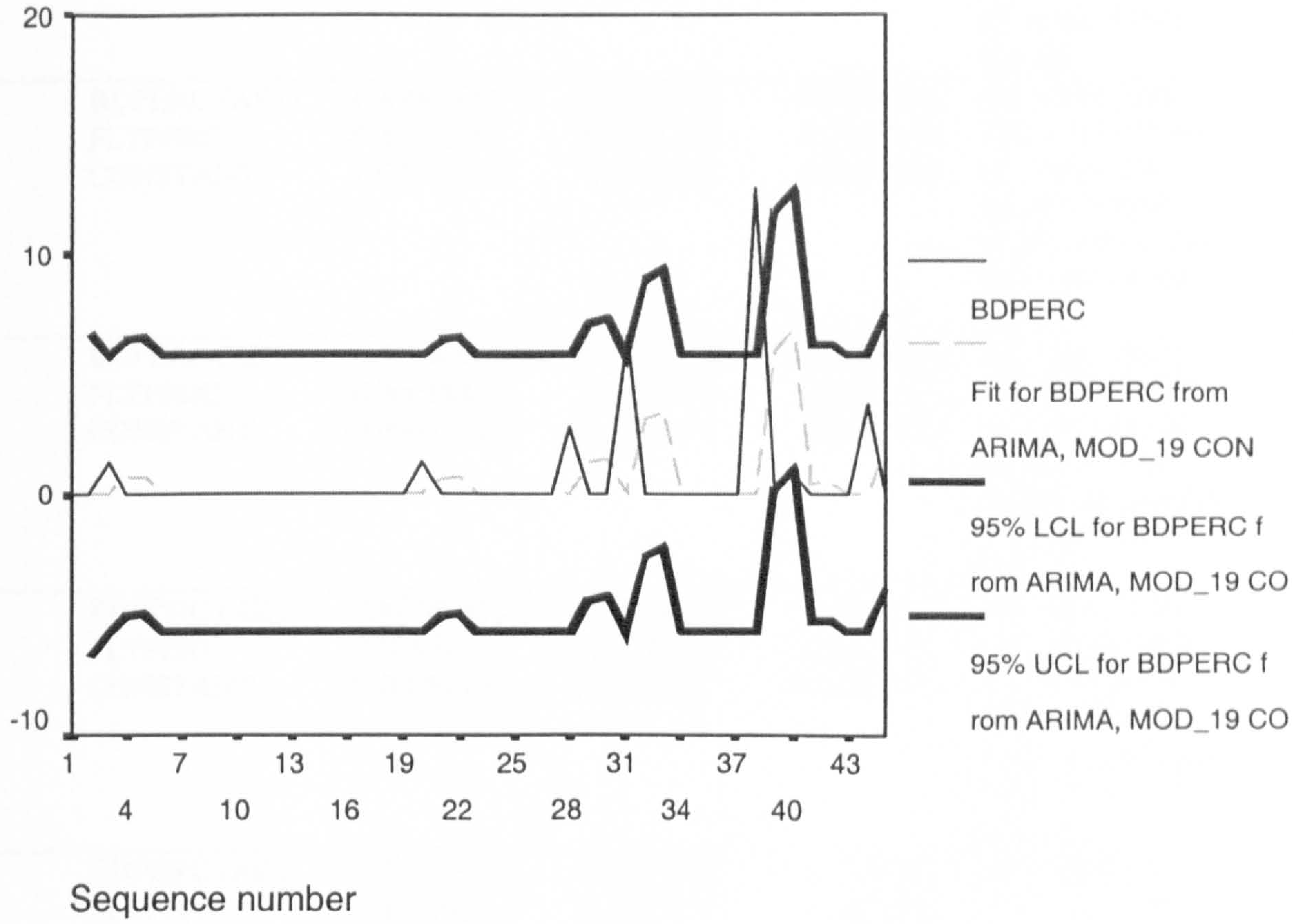


Table 7.3 - ARIMA Statistics for the Six Plant Items (CASE I)

Plant No.	Variable	Beta	Standardised Beta	T- Ratio	Statistics
1	BDPERC (AR1)	-0.42587498	0.1400541	-3.0407898	AIC =384.73002
	FLTPERC	-0.34455067	0.0825896	-4.1418415	SBC = 399.95547
	CONSTANT	0.37251100	1.9678708	0.1892965	LL =-189.36501
					SE =18.481658
					RASS =14,068.279
					RV = 341.57167
					MA =0
2	BDPERC (AR1)	-0.49965092	0.1234988	-4.04576954	AIC =394.2194
	FLTPERC	-0.15491487	0.0535320	-2.8938734	SBC = 390.08259
	CONSTANT	0.02731015	1.1478458	0.0237925	LL =-194.1097
					SE =12.067887
					RASS =6884.2248
					RV = 145.63389
					MA =0
3	BDPERC (AR1)	-0.54045308	0.1216052	-4.4443245	AIC =461.78212
	FLTPERC	0.06688806	0.1052672	0.6353417	SBC =467.51819
	CONSTANT	-0.09977182	2.1958879	-0.0454358	LL =-227.89106
					SE =23.703539
					RASS =26,590.389
					RV = 561.855777
					MA =0
4	BDPERC (AR1)	-0.44586925	0.13058337	-3.41444118	AIC =364.69496
	FLTPERC	-0.03351514	0.03593165	-0.93274712	SBC = 370.49044
	CONSTANT	0.00000000	0.81587087	-0.00000000	LL =-179.34748
					SE =8.3732401
					RASS =3,379.9926
					RV = 70.111149
					MA =0
5	BDPERC (AR1)	-0.21313905	0.1407640	-1.5141588	AIC =460.53448
	FLTPERC	-0.08211071	0.1179735	-0.6960095	SBC = 466.27055
	CONSTANT	-0.01883533	2.7480952	-0.0068540	LL =-227.26724
					SE =23.475777
					RASS =25,926.365
					RV = 551.11209
					MA =0
6	BDPERC (AR1)	-0.44534093	0.14178502	-3.1409589	AIC =208.77352
	FLTPERC	-0.04413880	0.01181990	-3.7342804	SBC = 214.12609
	CONSTANT	0.00378959	0.26288032	0.98856830	LL =-101.38676
					SE =2.5018998
					RASS =257.93221
					RV = 6.2595025
					MA =0

KEY:

AIC = Akaike Information Criterion
SBC = Schwartz Bayesian Criterion
LL = Log Likelihood
SE = Standard Error
RASS =Residuals Adjusted Sum of Squares
RV = Residual Variance
MA = Moving Average Parameter

Figure 7.8a – ACF Plot of the Residuals for BDPERC (CASE I)

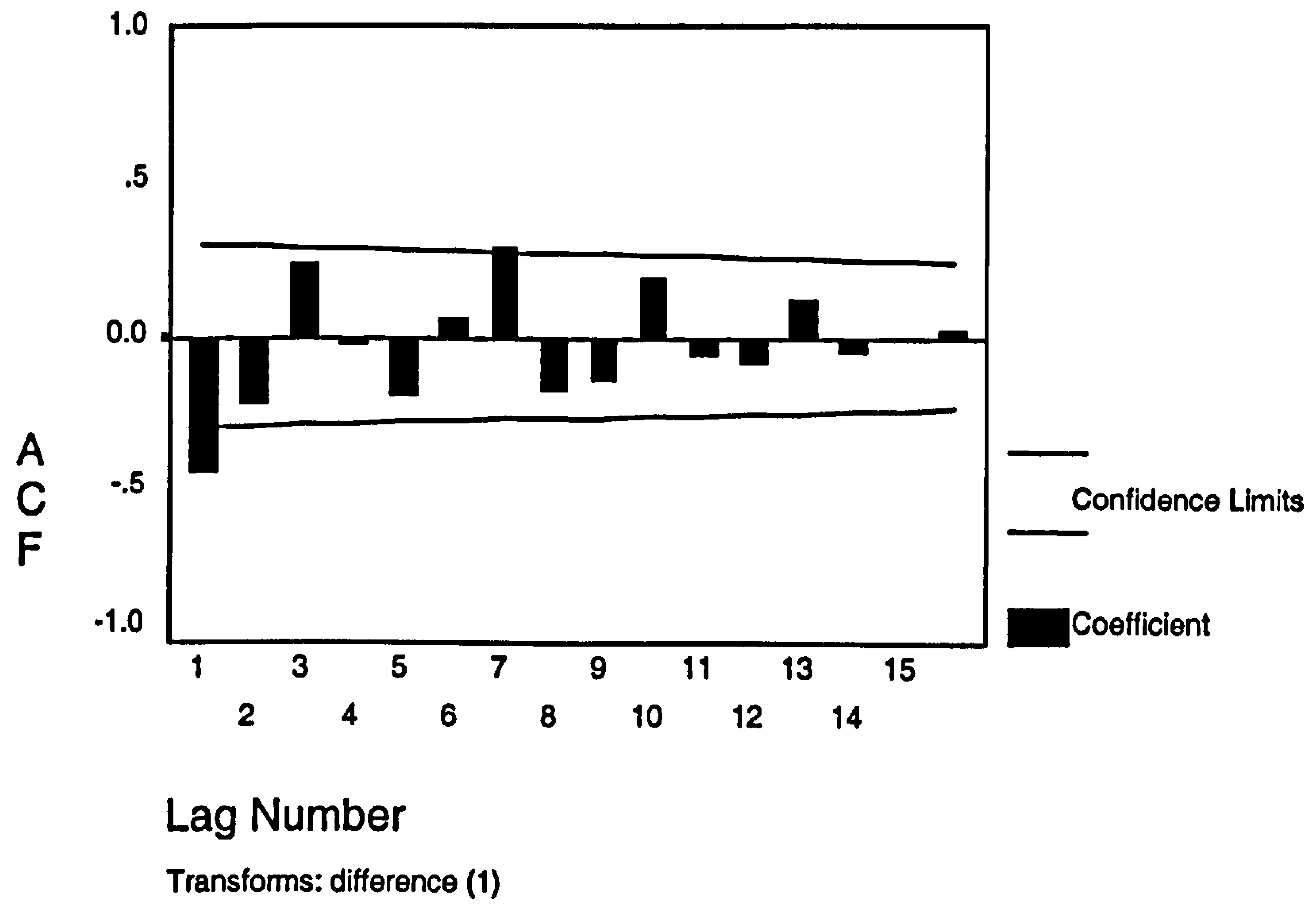
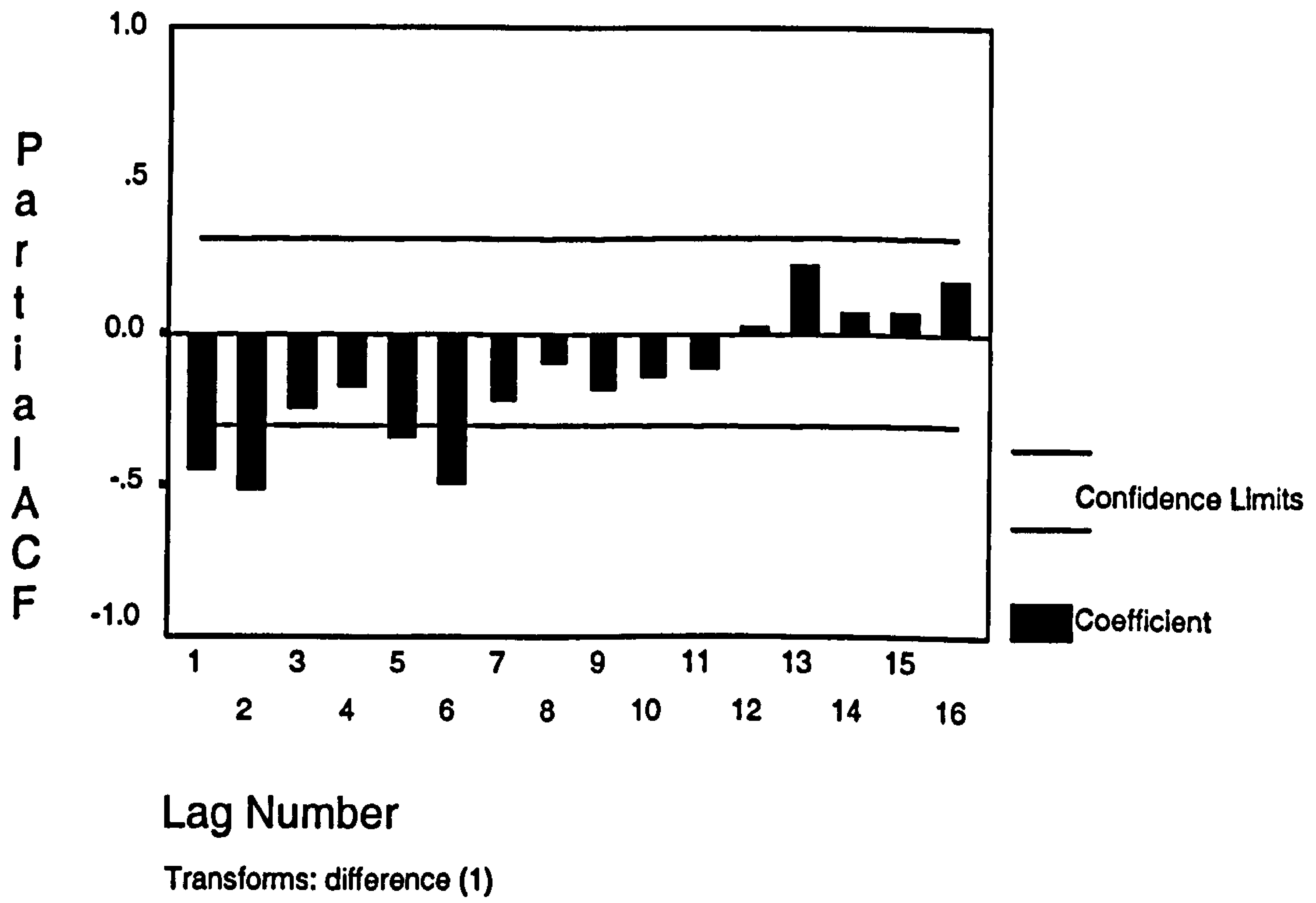


Figure 7.8b – PACF Plot of the Residuals for BDPERC (CASE I)



Based on these results, the ARIMA (1,1,0) model has the AR (1) parameter equal to 0.44534093. Other values (see Table 7.3) include: FLTPERC = -0.04413880 and

CONSTANT = 0.00378959. Therefore, the ARIMA (1,1,0) model for BDPERC (Case I) - based on equation 6.1 is:

$$BDPERC_{(t)} = CONSTANT + (-0.44534093) \times BDPERC_{(t-1)} + (0.04413880) \times (FLTPERC)_{(t-1)} + e_{(t)} \quad \ldots\ldots\ldots\ldots \tag{7.2}$$

Hence, the percentage breakdown for week 47 can be forecast as follows:

$$BDPERC_{(47)} = 0.00378959 + (-0.44534093) \times (3.81) + (0.04413880) \times (5.77) + 2.5018998$$

$$BDPERC_{(47)} = 1.06 \text{ per cent}$$

Using this equation, the model predicts that the percentage breakdown time (in hours) at week 47 will be approximately one per cent of the total hours the machine would be available in that week.

CASE II: Lagged BDPERC, FLTPERC and SBPERC as Independent Variables – (Model Estimation)

The second case was established by considering the lagged BDPERC, FLTPERC and SBPERC as independent variables. The plots of the fit curves for this series are shown in figures 7.8a and 7.8b for the estimation and validation periods respectively. These were based on an ARIMA (1,1,0) process. The plots illustrate the matching trends of the fit for BDPERC mostly within the estimation period (weeks 2 to 33). During this period the BDPERC fit curve showed matching trends with the actual records and fell reasonably well within the 95 per cent upper and lower confidence limits (figure 7.9a). However, an observation of the performance of the curve during the validation period revealed inherent weaknesses within the predictive capabilities of the case II model beyond the estimation period (figure 7.9b). For example, the actual breakdown percentages grossly exceeded those predicted by the model between week numbers 37 and 39. Although considering the performance of the case I model during these observation points, it could be inferred that there was the possibility of the influence of some 'outside events' that had no 'occurrence history' within the previous weeks. However, this assumption could only hold validity if the trend is repeated during those observation points when other cases have been fully evaluated.

Figure 7.9a: Fit Curve – Estimation Period Only (Case II)

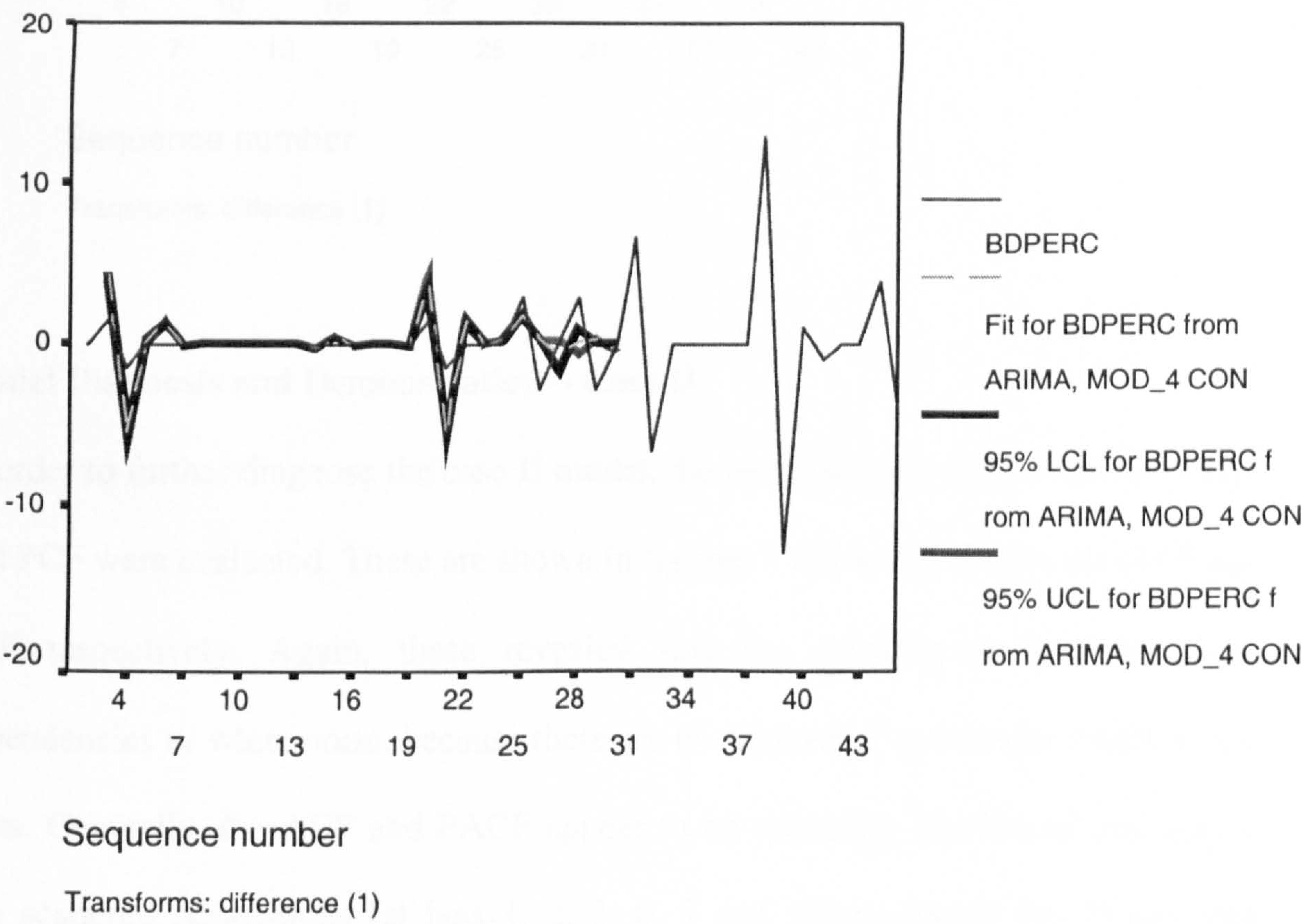
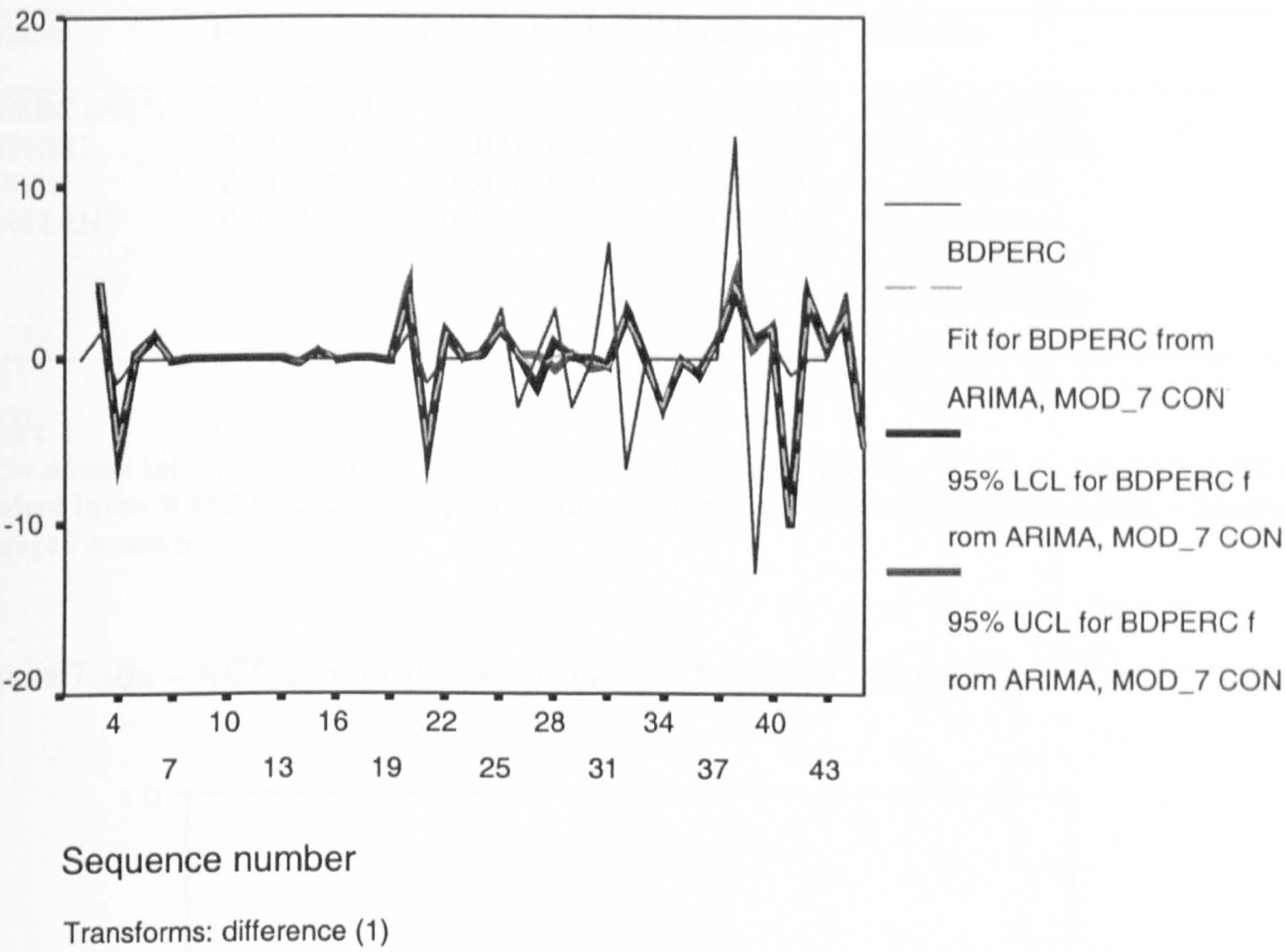


Figure 7.9b: Fit Curve - Estimation and Validation Periods (Case II)



Model Diagnosis and Demonstration – Case II

In order to further diagnose the case II model, the residual plots for the model's ACF and PCF were evaluated. These are shown in figures 7.10a and 7.10b for the ACF and PCF respectively. Again, these revealed that the correlogram has no serial dependencies or white noise, because there are no 'observed' systematic trends in the plots. Generally, the ACF and PACF appear to be randomly distributed and only a few scattered correlations (at lags 1, 2, 3, 6, 7 and 10) exceeded the 95 per cent confidence limits. Furthermore, the Box-Ljung statistic for the ACF function was not statistically significant at any lag with the standard error estimate being 2.442.

Table 7.4 - ARIMA Statistics Plant No. 6 (Case II)

Variable	Beta	Standardised Beta	T- Ratio	Statistics
BDPERC (AR1)	-0.46377311	0.14580673	-3.1807387	AIC =207.66878
FLTPERC	-0.04859808	0.01183492	-4.1063299	SBC = 214.80554
SBPERC	-0.04237695	0.01764820	-2.4012051	LL =-99.83439
CONSTANT	0.01935334	0.25352634	0.0763366	SE =2.4423744
				RASS =239.925
				RV = 5.9651929
				MA =0

KEY:
AIC = Akaike Information Criterion; SBC = Schwartz Bayesian Criterion; LL = Log Likelihood; SE = Standard Error; RASS =Residuals Adjusted Sum of Squares; RV = Residual Variance; MA = Moving Average Parameter

Figure 7.10a – ACF Plot of the Residuals for BDPERC (Case II)

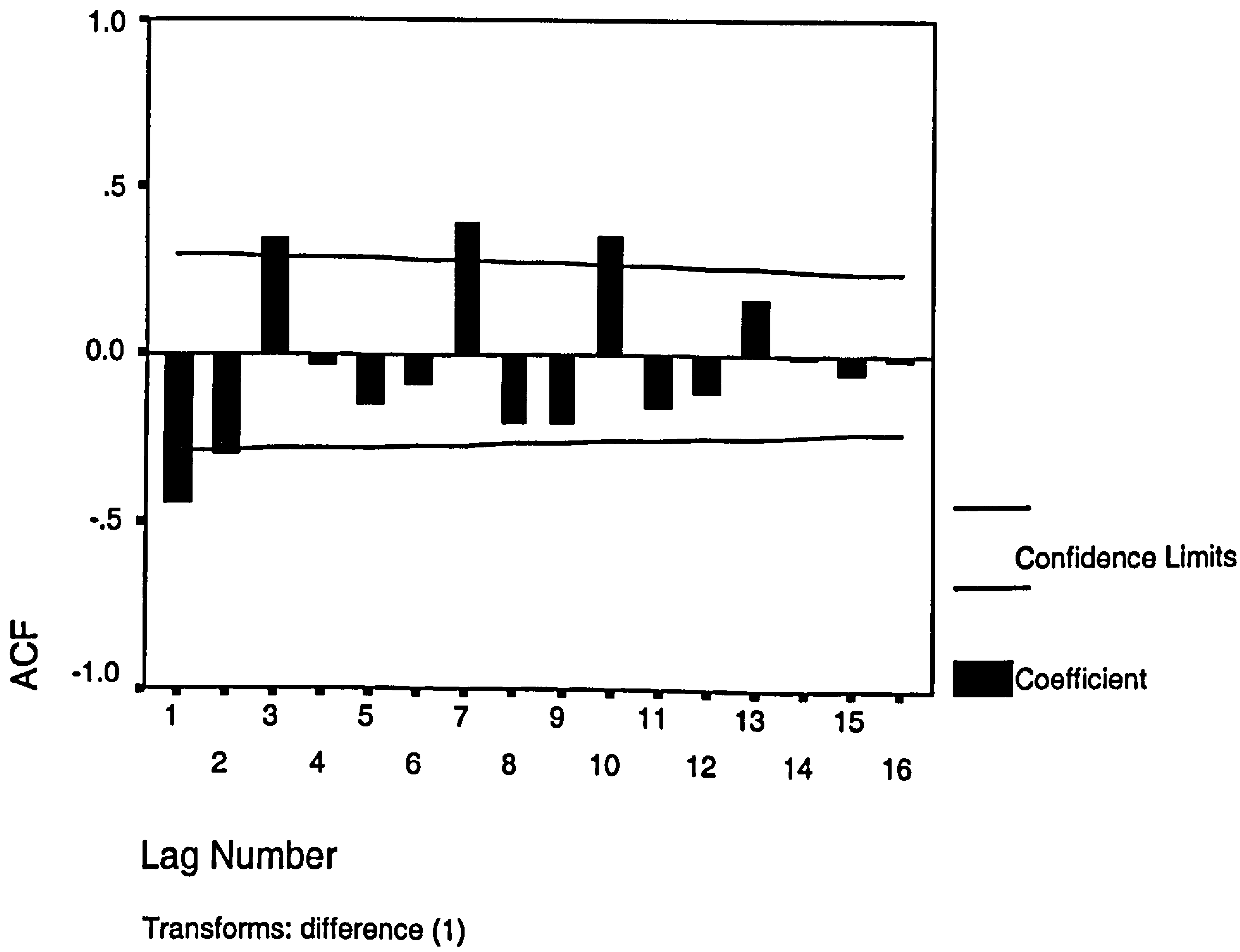
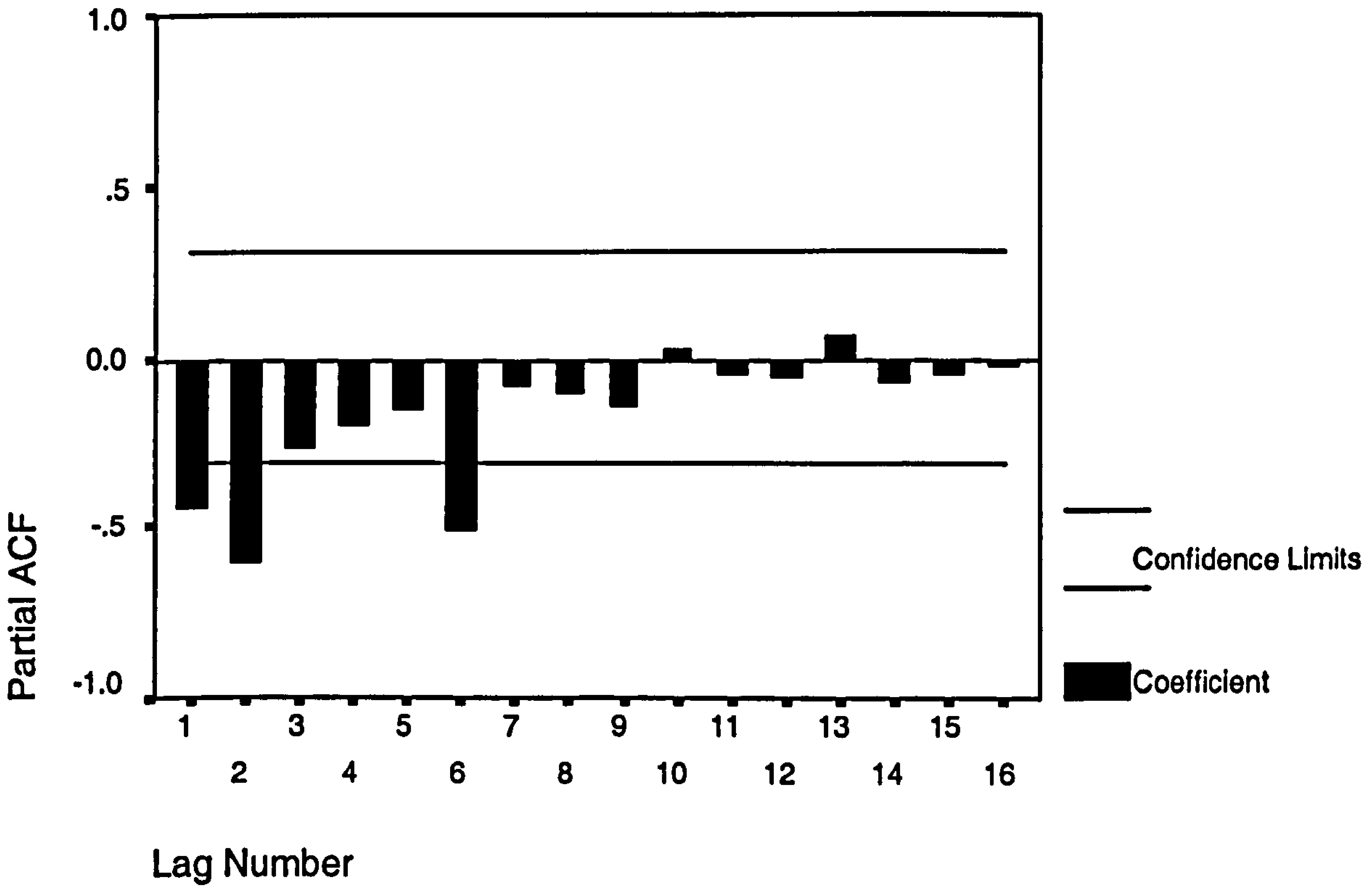


Figure 7.10b – PACF Plot of the Residuals for BDPERC (Case II)



Transforms: difference (1)

Therefore, the ARIMA (1,1,0) model was defined with the AR (1) parameter equal to -0.46377311 for case II. Other values (table 7.4) include: FLTPERC = -0.04859808; SBPERC = -0.04237695 and CONSTANT = 0.01935334. Therefore, the ARIMA (1,1,0) model for BDPERC (Case II) - based on equation 6.1 is:

$$BDPERC_{(t)} = CONSTANT + (-0.46377311) \times BDPERC_{(t-1)} + (-0.04859808) \times (FLTPERC)_{(t-1)} + (-0.04237695) \times SBPERC_{(t-1)} + e_{(t)} \ldots\ldots\ldots\ldots \quad (7.3)$$

Hence, the percentage breakdown for week 47 can be forecast as follows:

$$BDPERC_{(47)} = 0.01935334 + (-0.46377311) \times (3.81) + (-0.04859808) \times (5.77) + (-0.04237695) \times (0.95) + 2.4423744$$

$BDPERC_{(47)} = 0.37$ per cent

Using this equation, the model predicts that the percentage breakdown time (in hours) at week 47 will be approximately 0.4 per cent of the total hours the machine would be available in that week.

CASE III: Lagged BDPERC, FLTPERC and UTILPERC as Independent Variables – (Model Estimation)

For the third case, the lagged BDPERC, FLTPERC and UTILPERC were considered as independent variables. The purpose of this was to evaluate the predictive capability of the ARIMA BDPERC model based the influence of the utilisation history of plant items. Diagrammatic plots of the 'fit curve' for this series are shown in figures 7.11a and 7.11b for the estimation and validation periods respectively. The plots illustrate the matching trends of the fit for BDPERC; falling reasonably well within the 95 per cent upper and lower confidence limits. The 'excessive' breakdowns observed between week numbers 37 and 39 were probably due to the influence of outside events, which had no history of occurrence within the previous weeks. However, the fit of the curve after this period was satisfactory.

Figure 7.11a: Fit Curve – Estimation Period Only (Case III)

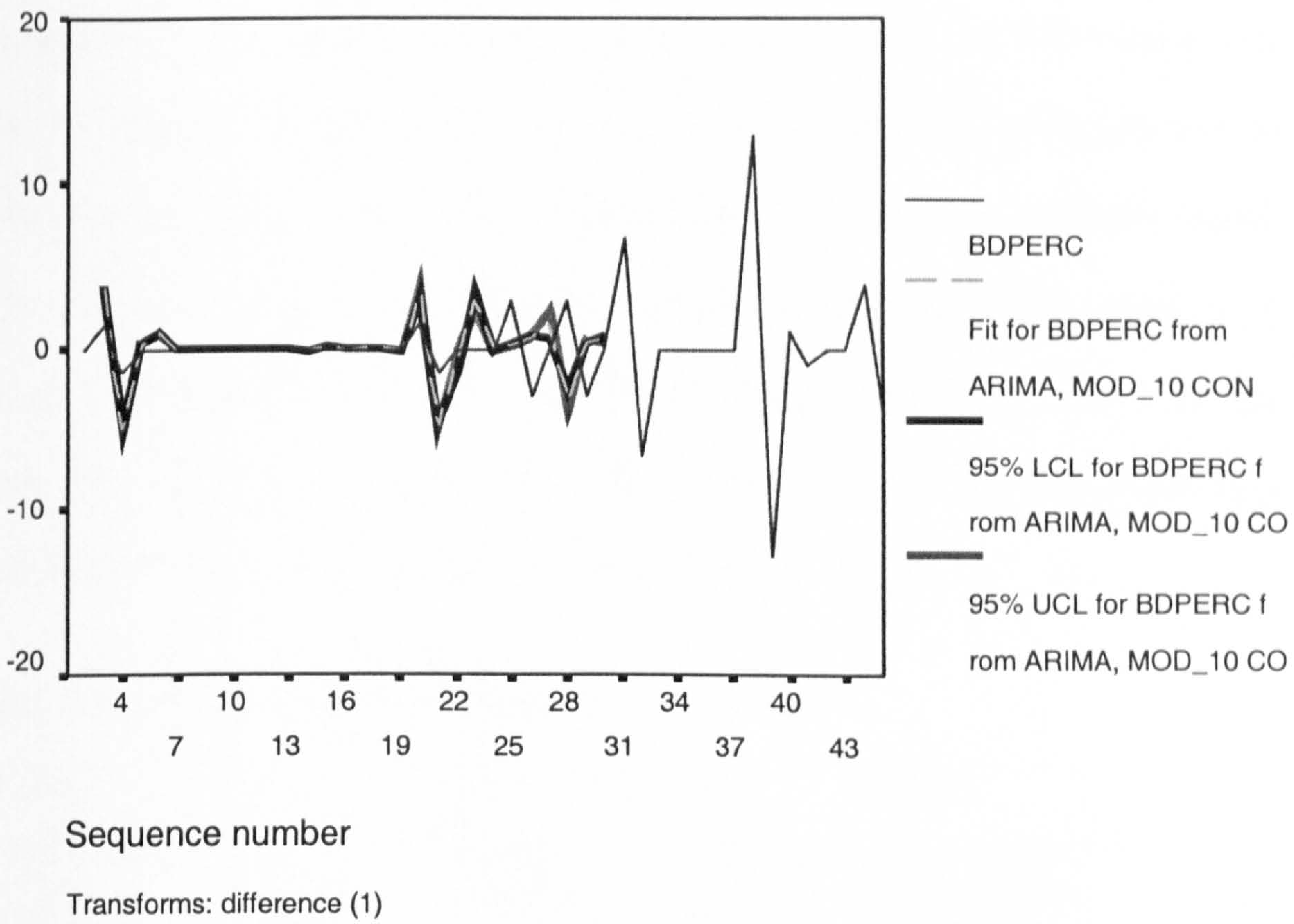
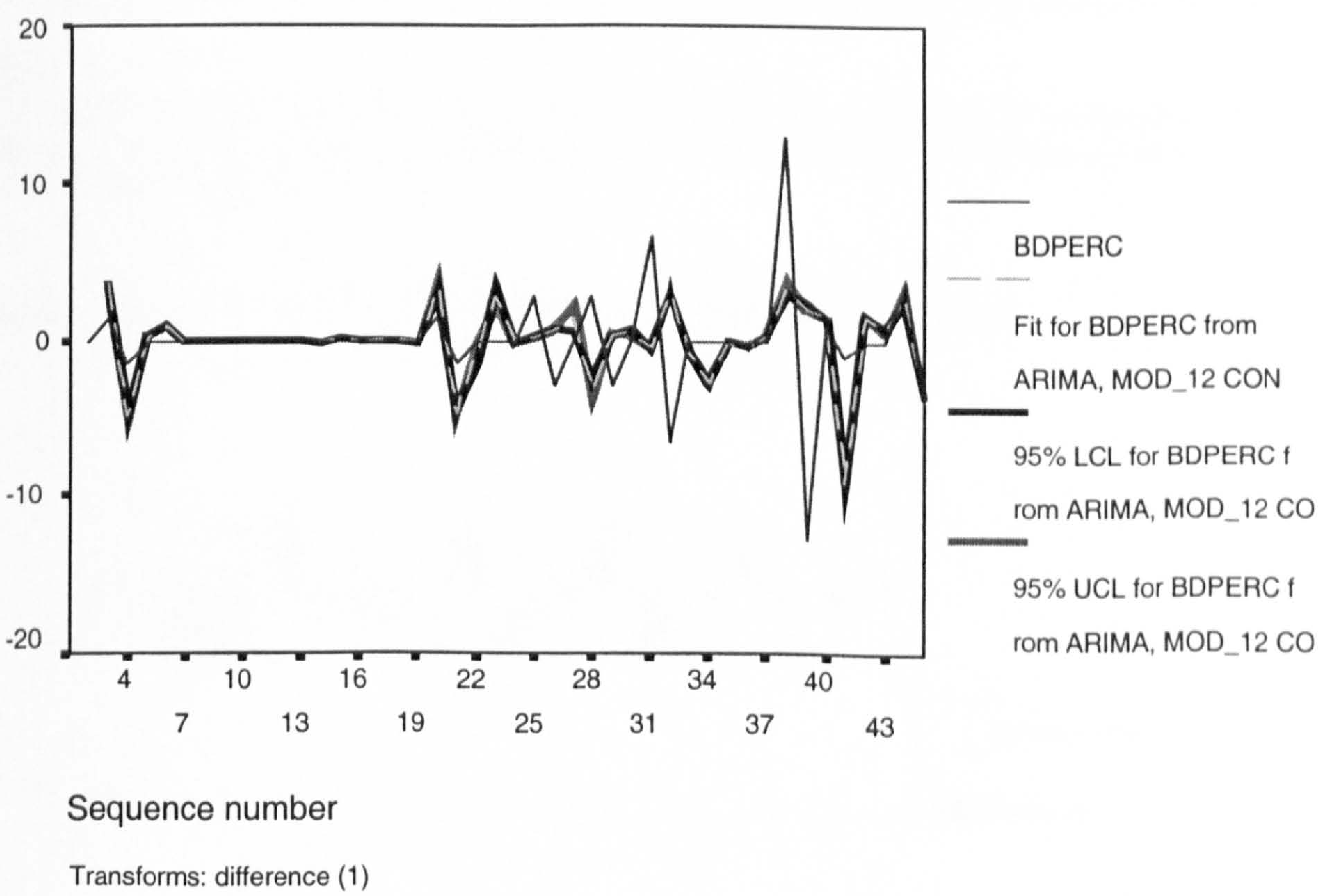


Figure 7.11b: CASE III Fit Curve - Estimation and Validation Periods (Case III)



Model Diagnosis and Demonstration – Case III

Residual plots for the case II model are shown for the ACF and PCF respectively (refer to Figures 7.12a and 7.12b). Again, these reveal that the correlogram has no serial dependencies or white noise, because there are no 'observed' systematic trends in the plots. As it was observed for cases I and II, the ACF and PACF appear to be randomly distributed and only a few correlations exceeded the 95 per cent confidence limits. The Box-Ljung statistic for the ACF function was also not statistically significant at any lag with the standard error estimate being 2.577.

Table 7.5 - ARIMA Statistics for Plant No. 6 (Case III)

Variable	Beta	Standardised Beta	T- Ratio	Statistics
BDPERC (AR1)	-0.42112223	0.14814849	-2.8871184	AIC =212.33917
FLTPERC	-0.04500055	0.01221854	-3.6829728	SBC = 219.47593
UTILPERC	-0.01564767	0.01513621	1.0337908	LL =-102.16958
CONSTANT	0.01050065	0.27407738	0.0383127	SE =2.5765723
				RASS =266.771
				RV = 6.6387249
				MA =0

KEY:
AIC = Akaike Information Criterion; LL = Log Likelihood; SE = Standard Error; RV = Residual Variance; SBC = Schwartz Bayesian Criterion RASS =Residuals Adjusted Sum of Squares MA = Moving Average Parameter

Figure 7.12a – ACF Plot of the Residuals for BDPERC (Case III)

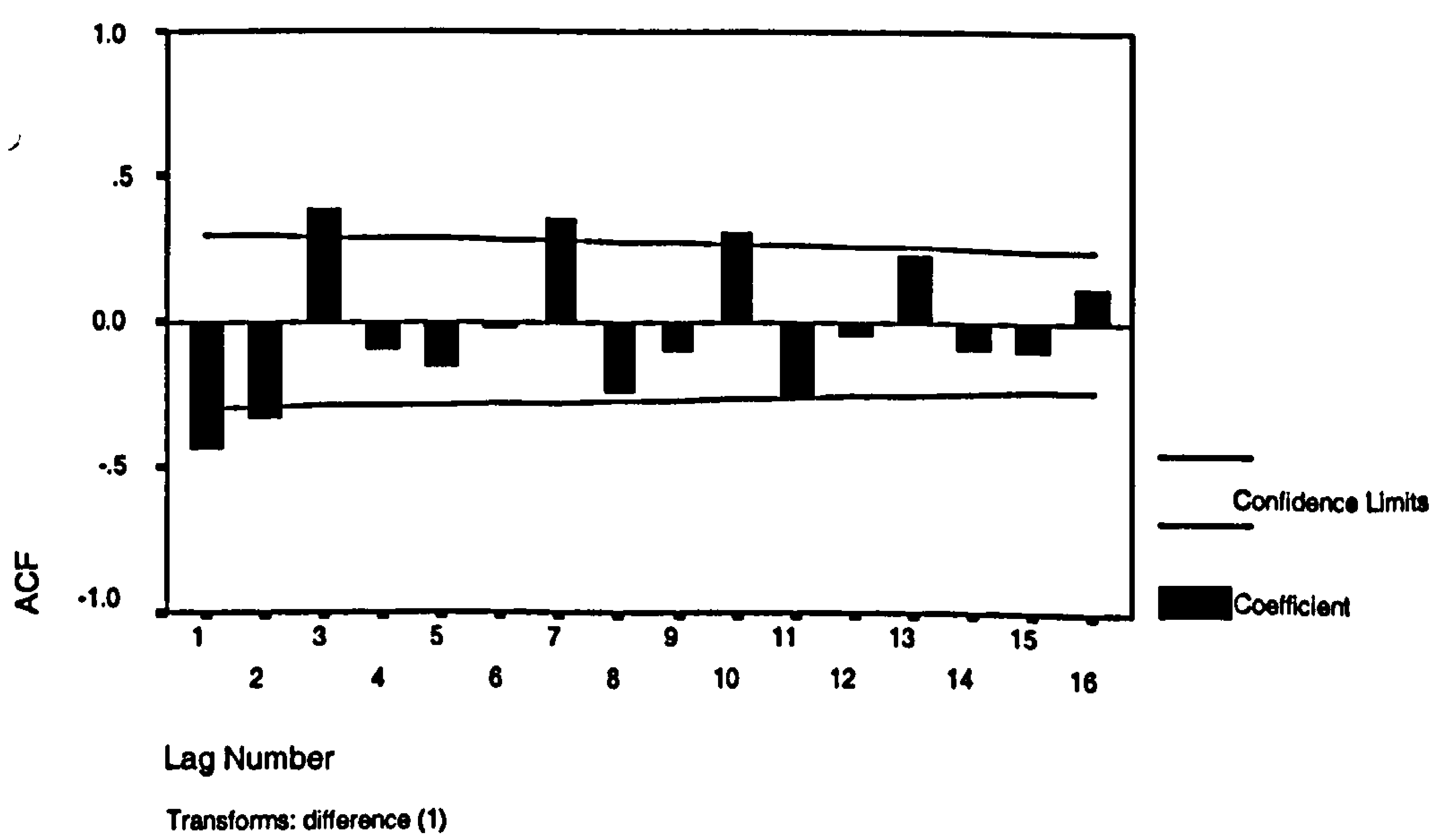
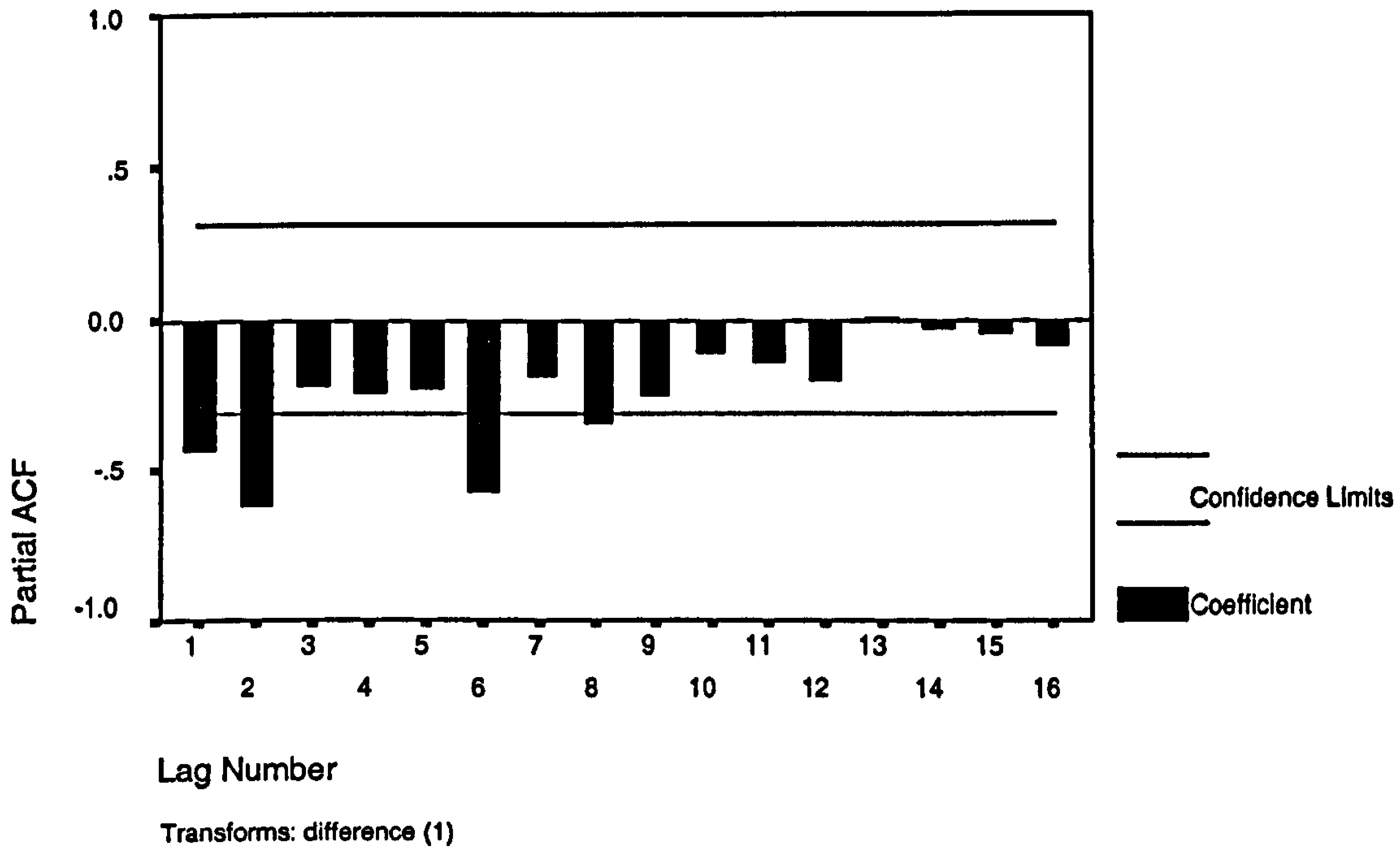


Figure 7.12b – PACF Plot of the Residuals for BDPERC (Case III)



For Case III, therefore, the ARIMA (1,1,0) model was defined with the AR (1) parameter equal to -0.42772233. Other values (table 7.5) include: FLTPERC = -0.04500055; UTILPERC = -0.01564767 and CONSTANT = 0.01050065. Therefore,

$$BDPERC_{(t)} = CONSTANT + (-0.42772233) \times BDPERC_{(t-1)} + (-0.04500055) \times (FLTPERC)_{(t-1)} + (-0.1564767) \times (UTILPERC)_{(t-1)} + e_{(t)} \ldots\ldots\ldots\ldots \quad (7.4)$$

Hence, the percentage breakdown for week 47 can be forecast as follows:

$$BDPERC_{(47)} = 0.01050065 + (-0.42772223) \times (3.81) + (-0.04500055) \times (5.77) + (-0.01564767) \times (95.24) + 2.5765723$$

$$BDPERC_{(47)} = 0.79 \text{ per cent}$$

Therefore, using this equation, the model predicts that there will be 0.79 percent breakdown time (in hours) at week 47.

CASE IV: Lagged BDPERC, FLTPERC, UTILPERC and SBPERC as Independent Variables – (Model Estimation)

As a fourth case consideration, the lagged BDPERC, FLTPERC, UTILPERC and SBPERC were considered as independent variables for the BDPERC prediction model. Using the software, the plots of the 'fit curve' for the case IV series are shown in figures 7.13a and 7.13b for the estimation and validation periods respectively. The plots illustrate the matching trends of the fit for BDPERC based on the combination of the four independent variables. This curve fits reasonably well within the 95 per cent upper and lower confidence limits and also this model gave the most reasonable predictions for the 'excessive' breakdowns observed between week numbers 37 and 39.

Figure 7.13a: Fit Curve – Estimation Period Only (CASE IV)

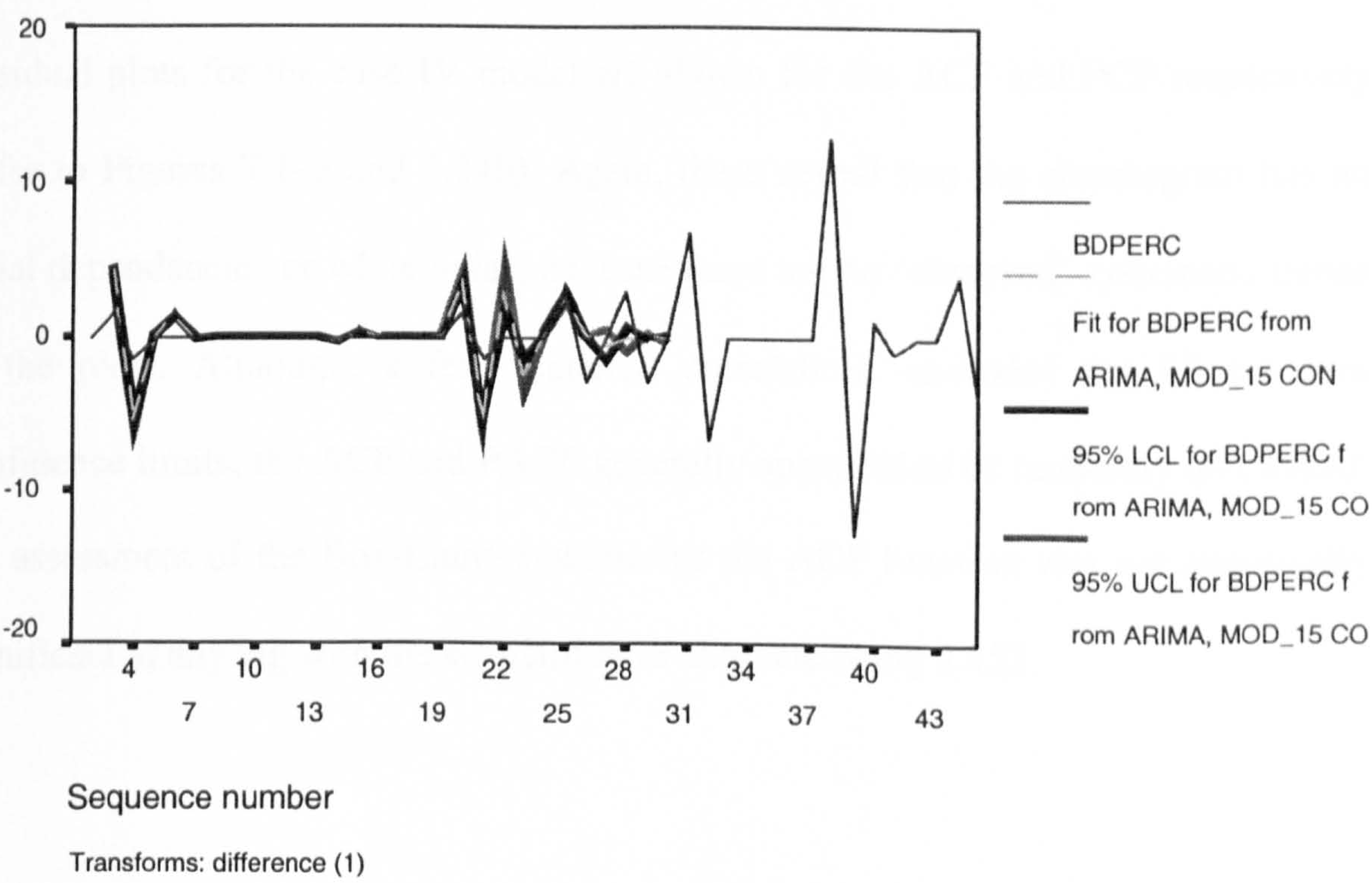
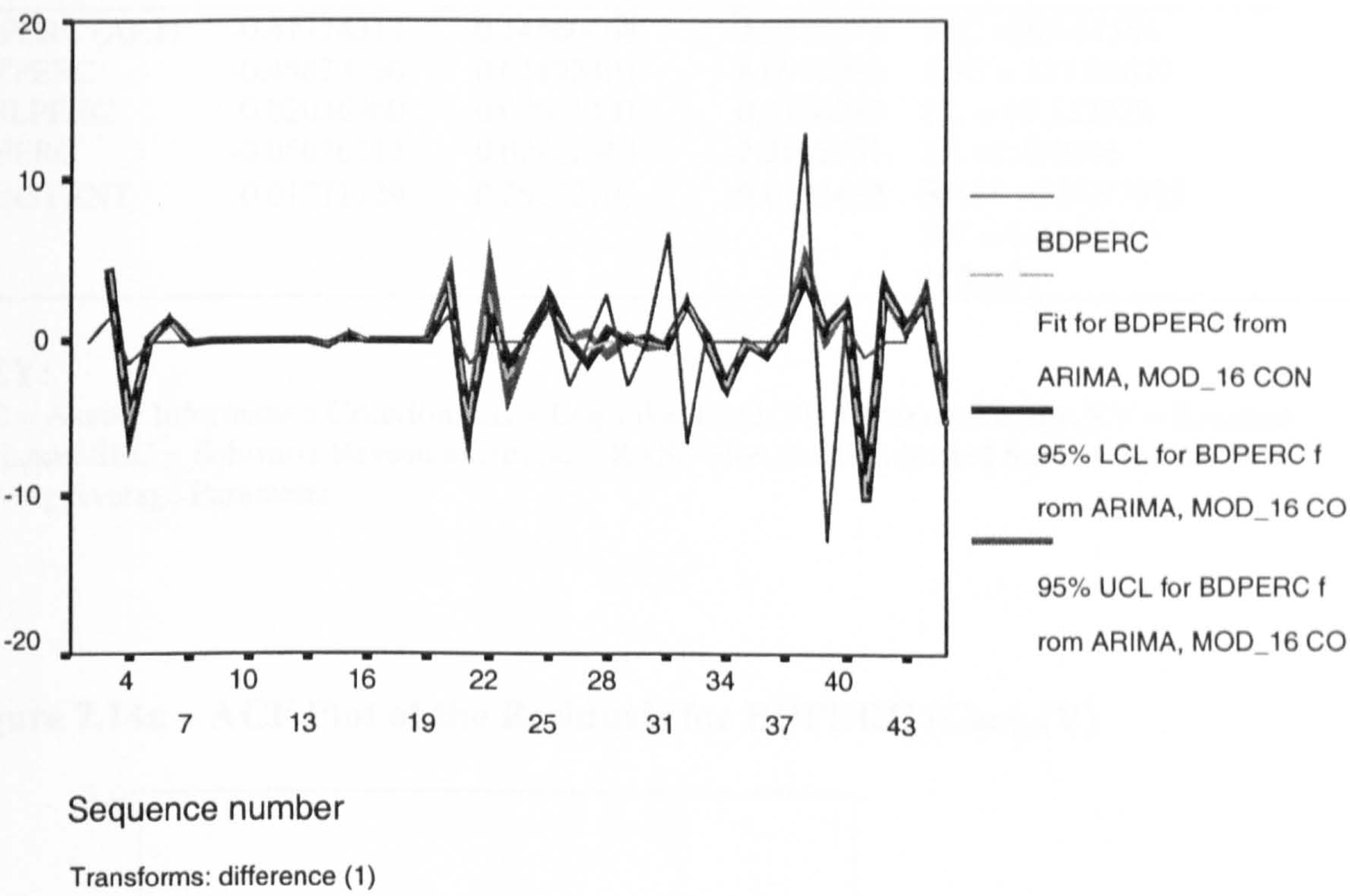


Figure 7.13b: Fit Curve - Estimation and Validation Periods (CASE IV)



Model Diagnosis and Demonstration – Case IV

Residual plots for the case IV model are shown for the ACF and PCF respectively (refer to Figures 7.14a and 7.14b). Again, these reveal that the correlogram has no serial dependencies or white noise, because there are no 'observed' systematic trends in the plots. Although, a few scattered correlations exceeded the 95 per cent confidence limits, the ACF and PACF generally appeared to be randomly distributed. An assessment of the Box-Ljung statistic for the ACF function was not statistically significant at any lag with the standard error estimate being 2.452.

Table 7.6 - ARIMA Statistics Plant No. 6 (Case IV)

Variable	Beta	Standardised Beta	T- Ratio	Statistics
BDPERC (AR1)	-0.47774312	0.14560468	-3.2810973	AIC =209.04584
FLTPERC	-0.48823160	0.01193401	-4.0910952	SBC = 217.96679
UTILPERC	0.02036960	0.02011401	0.8136289	LL =-99.522922
SBPERC	-0.05676213	0.02482863	-2.2861561	SE =2.452596
CONSTANT	0.01771729	0.25222793	0.0702432	RASS =235.97925
				RV = 6.0152269
				MA =0

KEY:
AIC = Akaike Information Criterion; LL = Log Likelihood; SE = Standard Error; RV = Residual Variance; SBC = Schwartz Bayesian Criterion; RASS =Residuals Adjusted Sum of Squares; MA = Moving Average Parameter

Figure 7.14a – ACF Plot of the Residuals for BDPERC (Case IV)

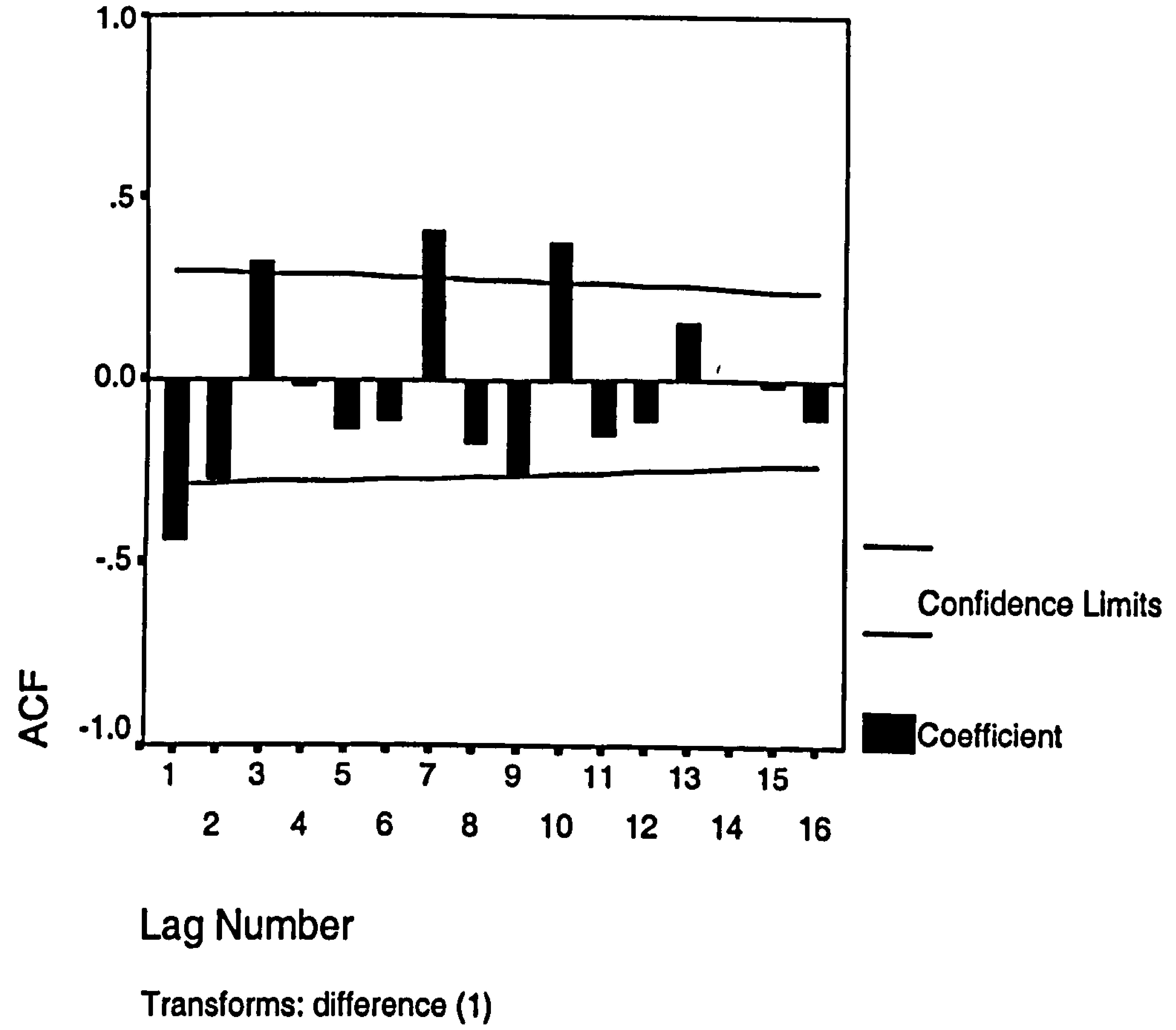
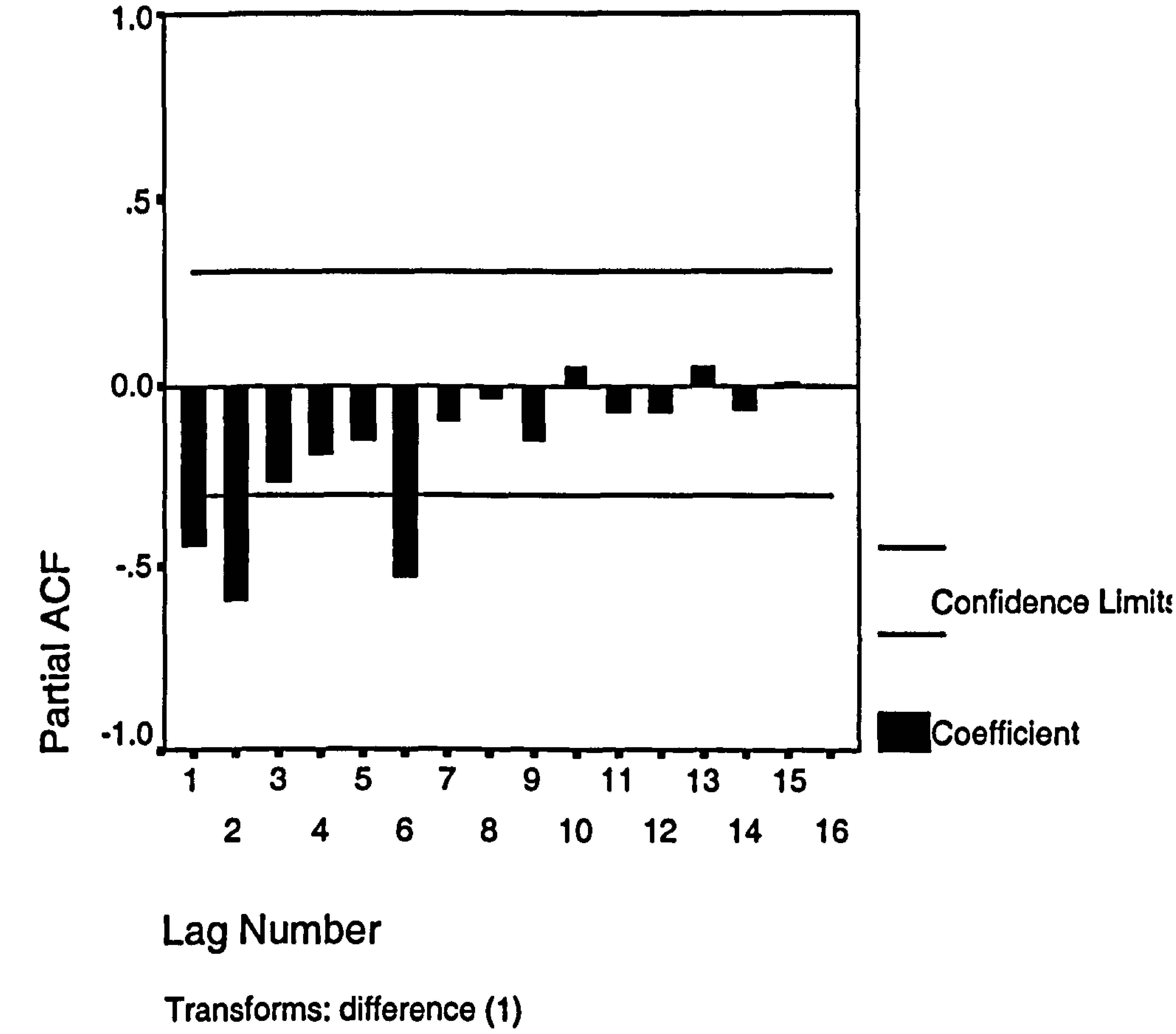


Figure 7.14b – PACF Plot of the Residuals for BDPERC (Case IV)



Therefore, for case IV, the ARIMA (1,1,0) model was defined with the AR (1) parameter equal to -0.47774312 for case IV. Other values (Table 7.6) include: FLTPERC = -0.48823160; UTILPERC = 0.02036960; SBPERC = -0.05676213; and CONSTANT = 0.01771729. Therefore, the ARIMA (1,1,0) case IV model for BDPERC (based on equation 6.1) is:

$$\begin{aligned} BDPERC_{(t)} = {} & CONSTANT + (-0.47774312) \times BDPERC_{(t-1)} + \\ & (-0.4882316) \times (FLTPERC)_{(t-1)} + (-0.01636534) \times \\ & (UTILPERC)_{(t-1)} + (-0.05676213) \times SBPERC_{(t-1)} + e_{(t)} \;\ldots.. \end{aligned} \qquad (7.5)$$

Hence, the percentage breakdown for week 47 can be forecast as follows:

$$BDPERC_{(47)} = 0.01771729 + (-0.47774312) \times (3.81) + (-0.4882316) \times (5.77) + (0.02036960) \times (95.24) + (-0.05676213) \times (0.95) + 2.452596$$

$$BDPERC_{(47)} = 0.26 \text{ per cent}$$

The case IV model yields 0.26 per cent, which gave the closest to the actual value of zero per cent. Additional investigations were, however, required to ascertain this.

DISCUSSION OF ANALYSIS RESULTS

In order to select the most appropriate model, analyses of all the results obtained were carried out. The analysis entailed a comparison of the obtained statistics for each model and also a comparison of the predicted results with the actual breakdown percentage obtained in the forecast week. A covariance analysis was then conducted to establish the level of the statistical control of the concomitant (independent) variables in the selected model.

Comparison of Results

The four cases investigated all indicated to be suitable ARIMA models for the prediction of BDPERC. Table 7.7 presents a summaries of the results obtained in respect of each case. Despite this result, however, further evaluation, is required in order to facilitate the selection of the 'best' model.

Table 7.7: Comparative Results for the BDPERC ARIMA model for CAT 908(6)

CASE	AIC	SBC	SE	PREDICTED BDPERC (%)	ACTUAL BDPERC (%)	REMARK
I	208.7	214.1	2.501	1.06	0.00	Least Suitable
II	207.7	214.8	2.442	0.37	0.00	Very Suitable
III	212.3	219.5	2.577	0.79	0.00	Suitable
IV	209.0	218.0	2.452	0.28	0.00	Most Suitable

KEY:
AIC = Akaike Information Criterion; SE = Standard Error; and SBC = Schwartz Bayesian Criterion

Based on table 7.7, the results obtained for cases IV, II and III and appear to be most suitable, very suitable and suitable respectively. This was in consideration of the closeness of the predicted BDPERC by the models to the actual BDPERC. Cases III and IV returned negative values which in practical terms indicate that the model predicts that there would be no breakdown event in the forecast week. Albeit, Case IV was preferred as it predicted the closest value to the actual BDPERC obtained in week 47 with over 90 percent accuracy. A covariance analysis was therefore conducted to serve as a confirmatory model selection procedure based on an analysis of the independent variables. Also, the validation of the predictive capability of this model and those developed for other plant types are presented in chapter eight.

Covariance Analysis for Independent Samples

Using the one-way analysis of covariance (ANCOVA) technique (Lowry, 1998), a critical investigation of cases I to IV was carried out. In each of the cases, the combination of the independent variables was examined to determine the case with the best correlation results. The ANCOVA also enabled a determination of the homogeneity between the independent variables. If homogeneity had been observed, the independent variables concerned would have been treated as one entity in the selected model. Results of the ANCOVA statistics are presented in table 7.8. These results indicated the display the values of the F-Statistics; the aggregate correlations between samples (r and r2); degree of freedom between regressions (dfreg); degree of freedom of the remainder (dfrem); and Mean Square Errors (MSE).

Table 7.8: Results from the ANCOVA for Cases I, II, II and IV

CASE	r	r^2	df_{reg}	df_{rem}	F	MSE
I	-0.31	0.10	1	86	130.46	242.62
II	-0.25	0.06	2	129	42.00	123.99
III	-0.19	0.04	2	129	44.02	130.76
IV	-0.17	0.03	3	172	24.89	87.42

In all cases, the F-statistics revealed that there is no homogeneity between the four variables. This is because the combinations of the df_{reg} and df_{rem} require F-statistics that are much smaller than the F-statistics obtained from the analysis in each case. In order for homogeneity conditions to be satisfied, the reverse should be obtainable. Hence each of the independent variables had a significant contribution to the dependent variable BDPERC. Furthermore, as a confirmation to the results obtained from the model estimated from the ARIMA procedure, case IV again proved to be the most reliable of the four. The best correlation result was obtained for this case and the mean square error was least for the combination of independent variables under this case.

Based on the foregoing the model developed under case IV, in which the lagged BDPERC, FLTPERC, UTILPERC and SBPERC was adopted as the most suitable for the prediction of BDPERC.

BENEFITS OF THE EXPLORATORY BDPERC MODEL

The developed exploratory model may be used for predicting weekly wheel loader plant breakdown time as a percentage of work time projected for individual plant items for that week. For the model to make this prediction, it utilises the most recent measurements of BDPERC, FLTPERC, UTILPERC and SBPERC in the case IV model (equation 7.5). This estimate enables management to make forecasts of the wheel loader breakdown time anticipated over the next observation period. This facilitates the development of contingency plans in the event that the prediction breakdown levels would be unacceptable to the work programme.

Also, the exploratory methodology utilised in its development has enabled the definition of an approach to modelling plant breakdown time for other often-utilised off-highway plant items. Extending the procedure to other items such as hydraulic tracked excavators, backhoe-loaders and off-highway haulers, can now facilitate the generation of other models. All the models will then be hosted within the model library of the INTELLIPLANT MBMS.

SUMMARY

The result of this exploratory study has led to the development of a plant breakdown prediction model using the time series analysis technique. Based on the historical dataset for the 6 wheel loaders selected, the procedure led to the identification of the ARIMA process as most suitable for the model development. After a rigorous analytical procedure using the SPSS trends (version 10) software, an ARIMA (1,1,0) model was identified. This model was used in an estimation procedure in which four separate cases of combinations of the independent variables, i.e. the lagged BDPERC, FLTPERC, UTILPERC and SBPERC were analysed via the ARIMA process. Case IV that had the combination of the four independent variables was selected due to closeness of its prediction to the actual value of BDPERC. Furthermore, the results of the ANCOVA procedure conducted facilitated the confirmation of the suitability of the selected model. This procedure also led to the determination of the homogeneity of the independent variables in the model. Therefore, the significant contributions of the individual (independent) variables on the dependent variable BDPERC, was ascertained.

The method used in the exploratory investigation was thus considered suitable for analysing the historical data on other plant items such as hydraulic tracked excavators, backhoe-loaders and off-highway haulers. This process culminated into the model library development of INTELLIPLANT MBMS.

CHAPTER EIGHT: INTELLIPLANT - The Model Base Management System

INTRODUCTION

The MBMS is designed to enhance the intelligent functionality of INTELLLIPLANT. Although the system (MBMS) could contain as many different types of models as possible, its primary objective is to facilitate decision support within an intelligent (database) system (Turban and Aronson, 2001; Bertino *et al*, 2001). This objective can be achieved by the MBMS enabling forecast/predictions based on historical data and/or performing other complicated analyses (Weiss and Indurkhya, 1998). The MBMS of INTELLIPLANT was therefore been conceived as a system containing a library of validated time series models that could enhance the prediction of plant breakdown percentage time as a function of actual time of work for the plant item.

Prior to the development of the time series model library, an exploratory analysis revealed the suitability of the ARIMA technique for plant breakdown prediction using based on a multivariate analysis. Of the four independent variables that made up the multivariate model, the lagged BDPERC is endogenous, while FLTPERC, UTILPERC and SBPERC are exogenous to the dependent variable (forecast BDPERC). This exploratory procedure was carried out on wheel loaders (chapter 7) and the findings constituted the basis upon which models for other plant equipment types were built. Specifically, the research concentrated on the development of breakdown prediction models for: wheel loaders, backhoe loaders, hydraulic excavators and off-highway loaders. This is because of the versatility and wide application of these types of equipment in various off-highway applications. A finding obtained from literature survey and field investigations during the study. The INTELLIPLANT MBMS was therefore designed to contain models developed based on several typical historical data from these types of off-highway plant items. The developed MBMS was therefore considered adequate for the enhancement of plant information management decision support within the off-highway plant sector.

This chapter critically examined the development process of the INTELLIPLANT MBMS that entailed the development of all the forecasting models for the three additional plant items; the validation of the four models; and the subsequent formulation and integration of the MBMS with the RDBMS. In establishing the MBMS, the research, therefore, examined the;

i) development of a set of models suitable for the objectives of INTELLIPLANT;
ii) setting up of a model base and directory structure;
iii) selection and development of a modelling language and model execution logic; and
iv) integration of the MBMS to the RDBMS through a VBA interface.

Overall attention was also paid to human-computer interaction (HCI)/GUI aspects, request processing speed and the accuracy of model execution within the MBMS environment.

DEVELOPMENT AND VALIDATION OF FORECASTING MODELS

In each of the plant history data utilised for the development of the breakdown percentage time prediction models, the procedure involved a three-stage simulation. This involved; a review of the historical data for the selected plant item; a time series analytical procedure based on the methodology established under the exploratory study; and the model development/ validation process. The methodologies adopted for the backhoe-loader, hydraulic excavator and off-highway hauler plant are now described.

Backhoe Loader Prediction Model

After a careful consideration of the available plant history data from the range of backhoe-loaders, the CAT 446B(3) was selected. It was considered as the most appropriate for model development based on the results of its performance statistics. Based on the time series modelling philosophy established as a result of the exploratory study, the lagged BDPERC, FLTPERC, UTILPERC and SBPERC were selected as the independent variables of the dependent variable. Plots of the sequence charts for BDPERC against time in weeks for historical data of the backhoe loader revealed a non-stationary and non-seasonal series. However, this series indicated stationarity after the first order transformation (achieved after first order differences). These observations are illustrated in Figures 8.1a and 8.2b for the CAT 446B(3) backhoe-loader.

Figure 8.1a – Sequence Plot for CAT 446 B(3) Backhoe-Loader (Original Data)

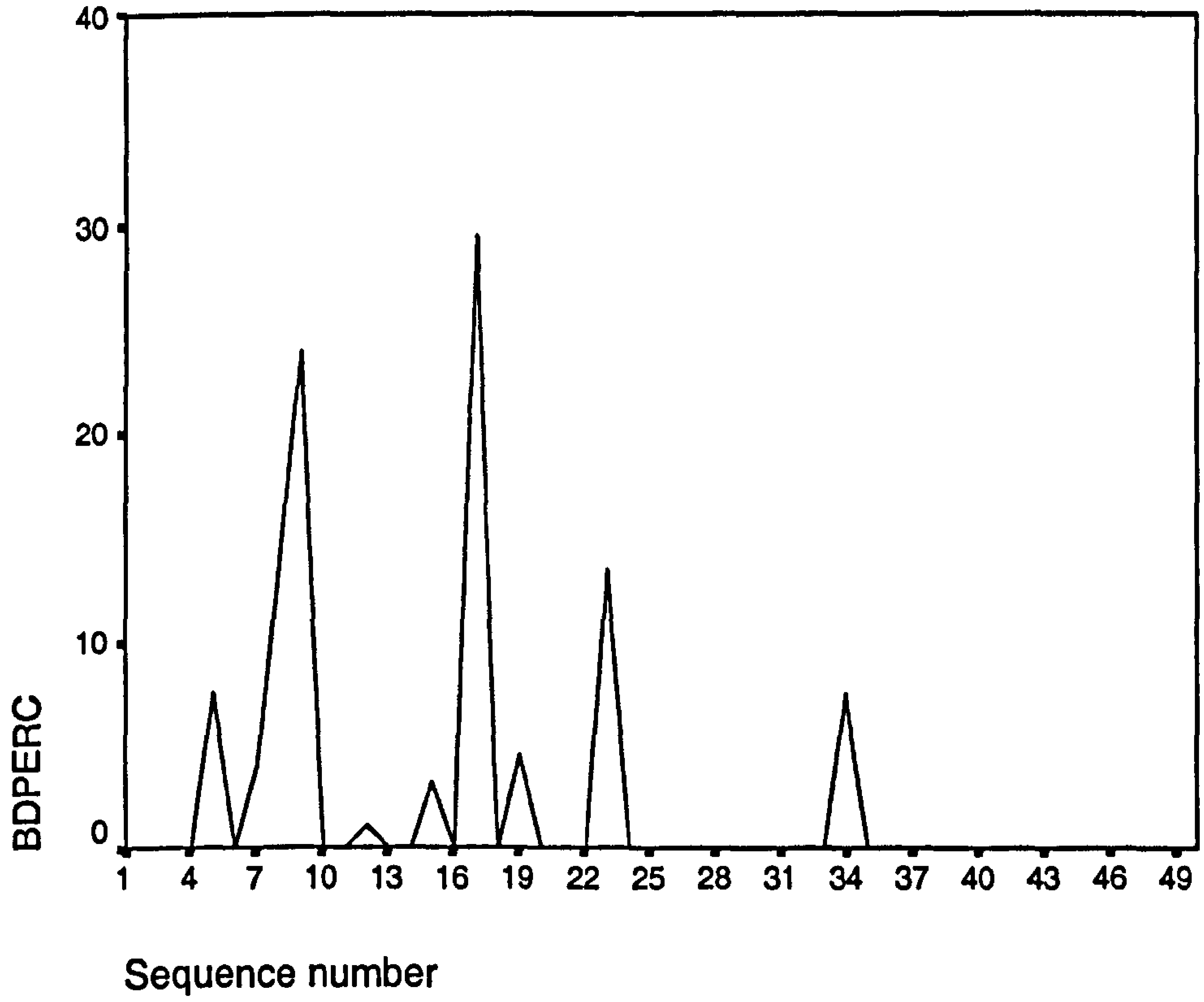
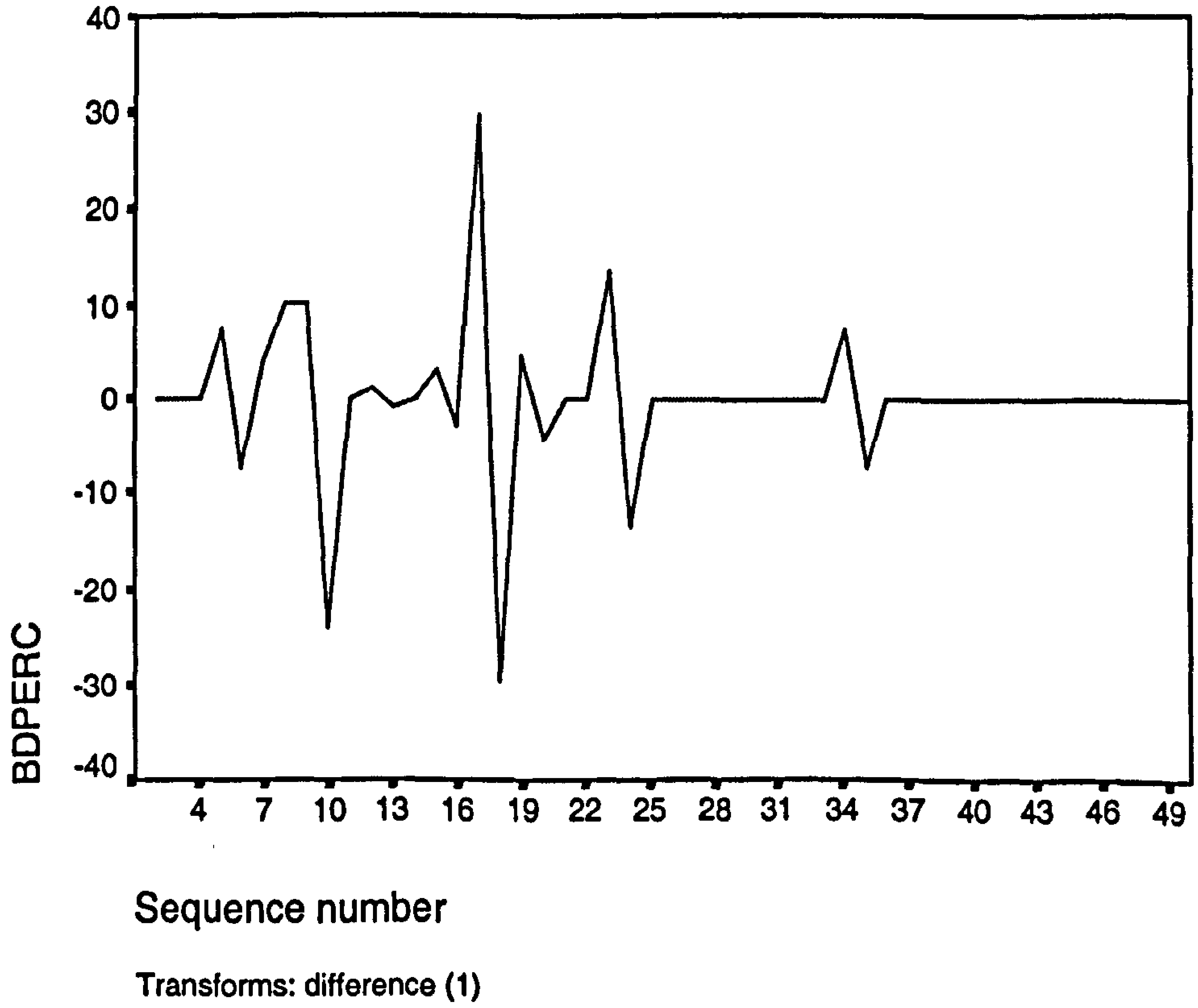
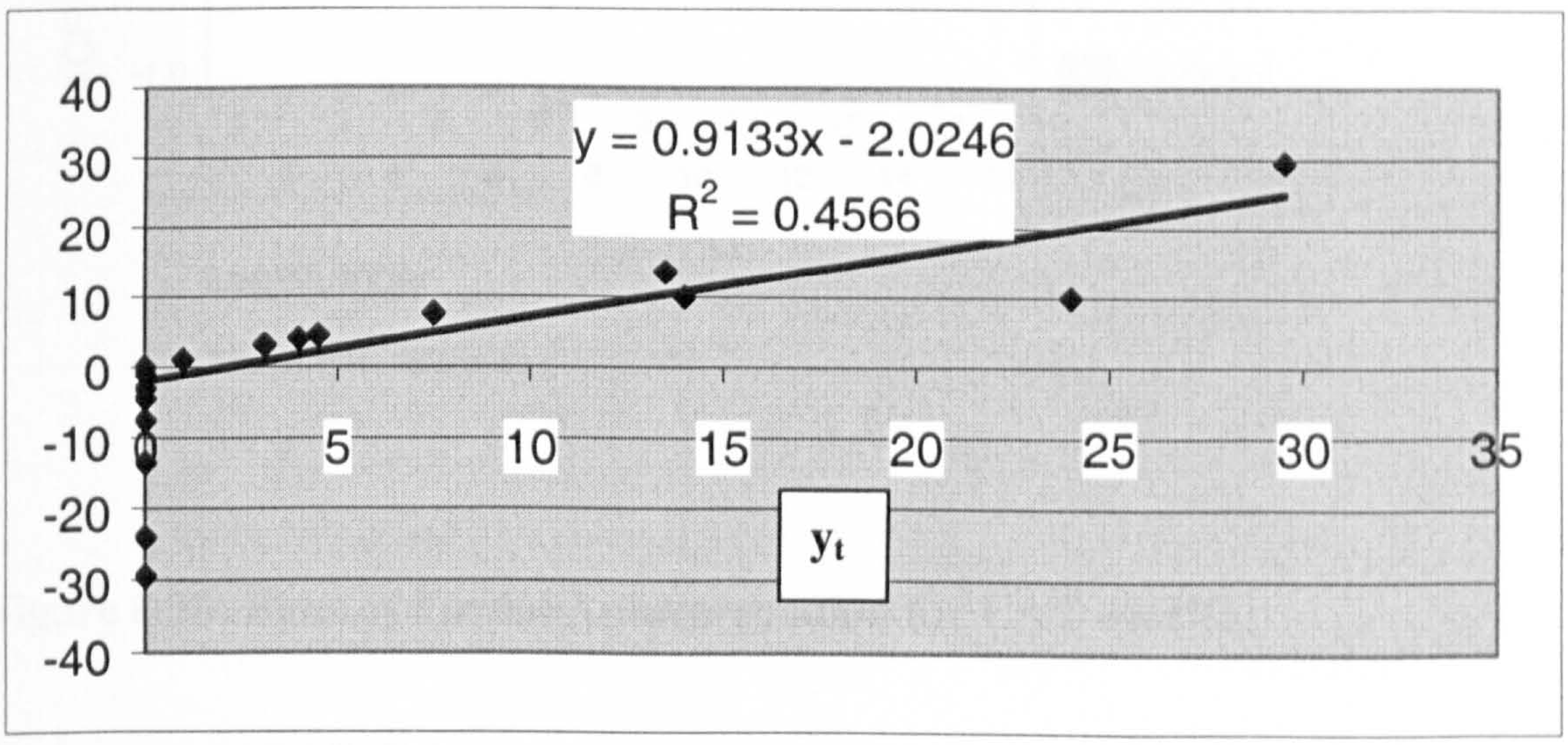


Figure 8.1b – Sequence Plot for CAT 446B(3) Backhoe-Loader (Transformed)



Furthermore, the Dickey Fuller test was also used to confirm the stationarity of the series by testing for unit roots. As demonstrated in Figure 8.2, regressing Δy_t on the lagged value of y_t yielded an estimated slope coefficient of 0.9133 and a t-statistic of –2.0246, which exceed the critical values of Figure 8.2. This result confirms the stationarity of the series after a first order differencing i.e. it is an ARIMA I(1) model.

Figure 8.2: Regression results of Δyt on yt for CAT 446B(3)



The plots for autocorrelation and partial autocorrelation functions are given in Figures 8.3a and 8.3b respectively. These were produced in order to determine the most suitable values for p and q, the autoregressive and moving average components of the ARIMA model. Both plots show a significant first spike and alternating value in the ACF for subsequent lags. A characteristic suitable for interpretation as an ARIMA AR (1) model with MA (0).

Figure 8.3a: Plots of Autocorrelation for CAT 446B(3)

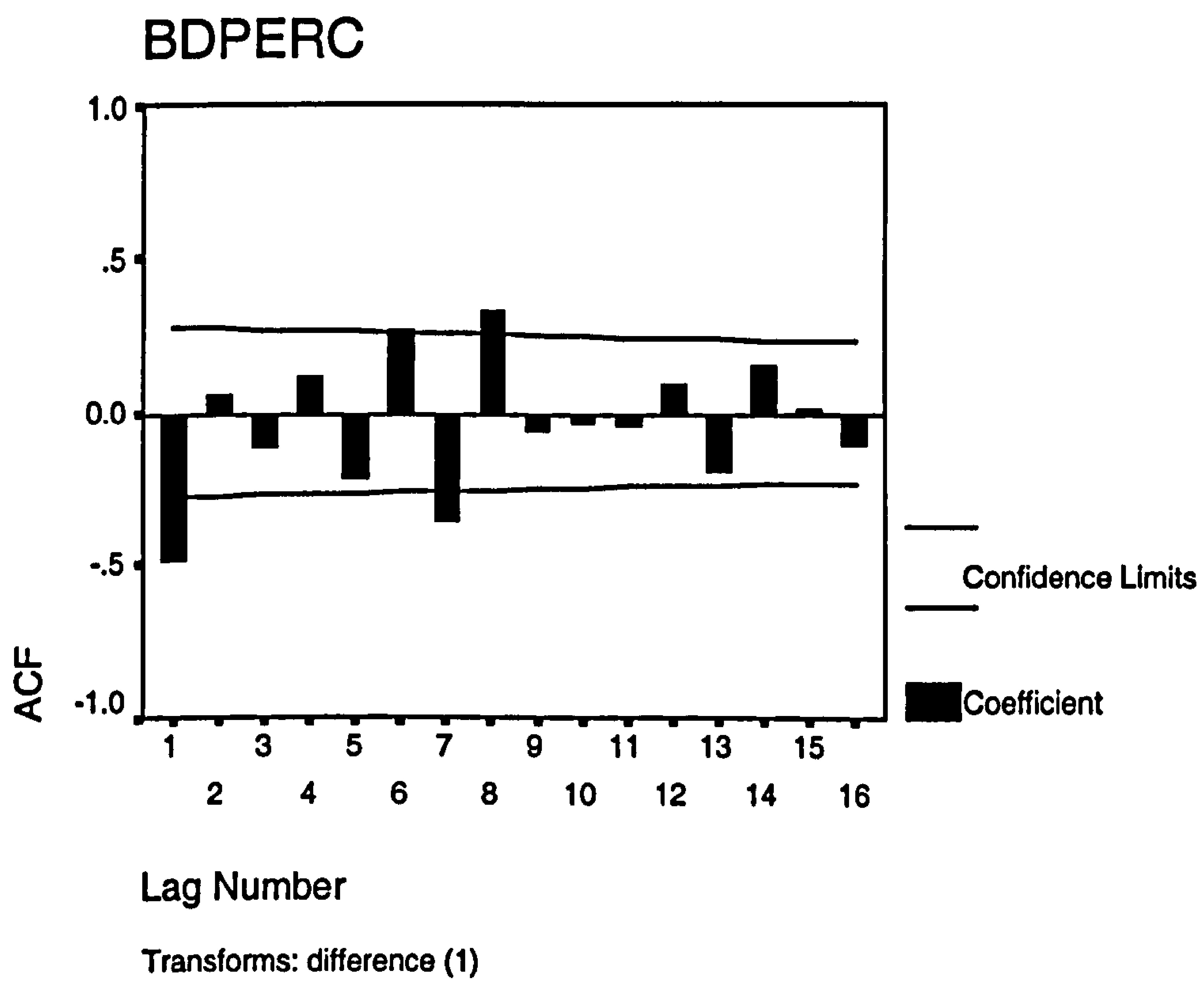
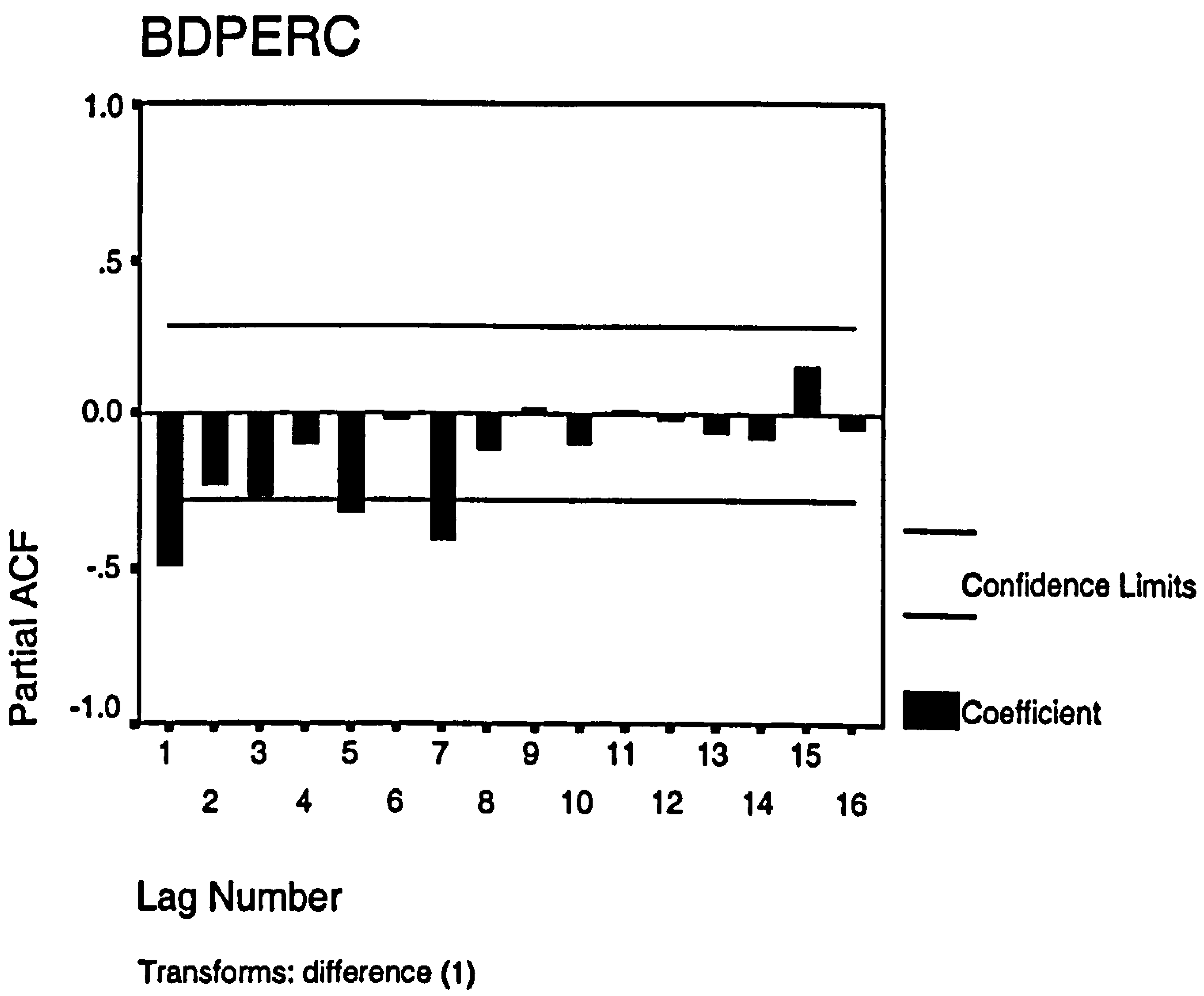


Figure 8.3b: Plots of Partial Autocorrelation for CAT 446B(3)



The SPSS Trends software was then used to analyse the ARIMA (1,1,0) model. The objective of the analysis is to observe the effect of the independent variable on the model's performance statistics and the fit curve. The approach to the analysis entailed a modelling of 75 percent population of the time series sample within a 99 percent confidence interval while holding out 25 percent for validation purposes. Results from the analysis are summarised in Table 8.1.

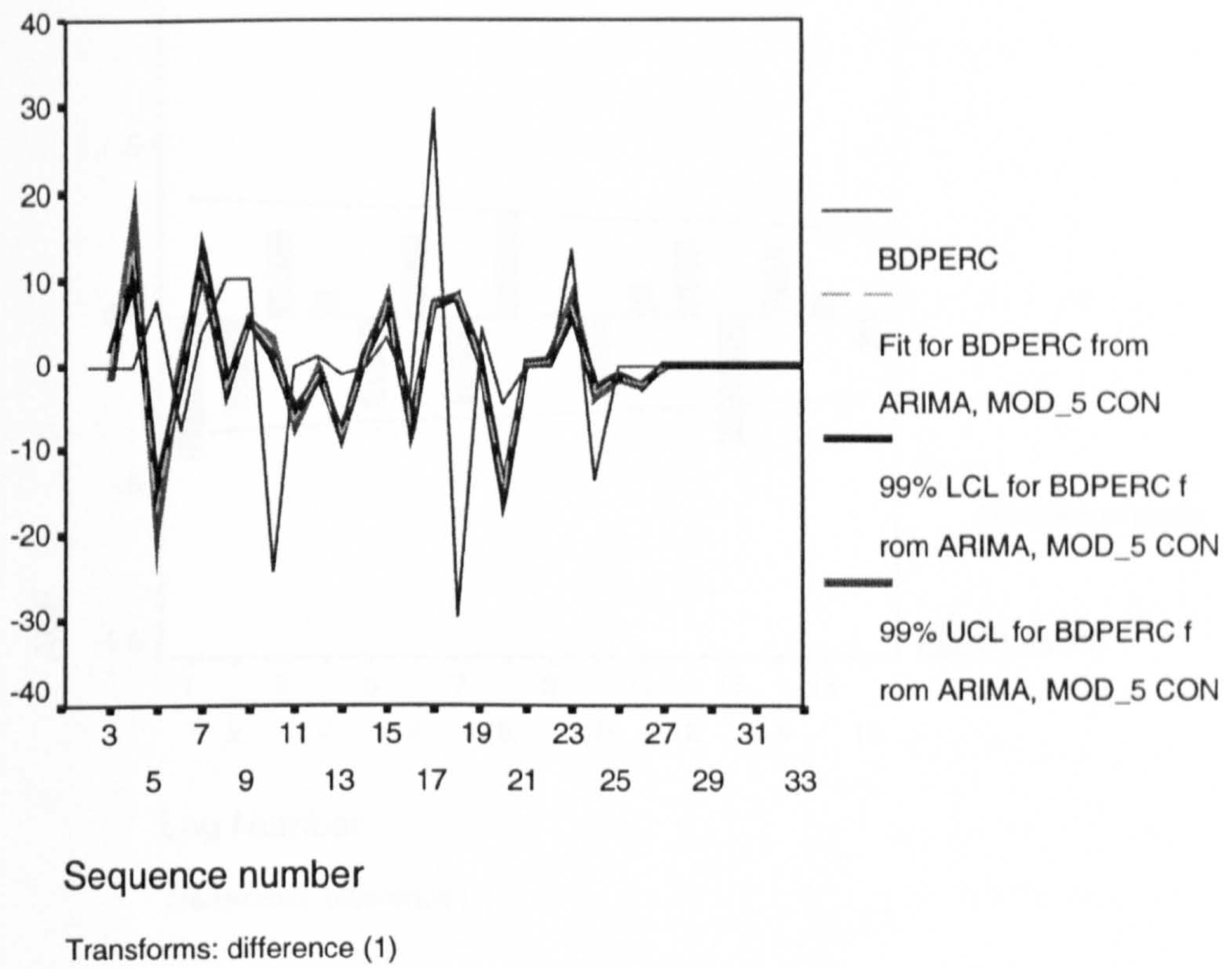
Table 8.1- ARIMA Statistics for the CAT 446B(3)

Variable	Beta	Standardised Beta	T- Ratio	Statistics
BDPERC (AR1)	-0.39221270	0.14515126	-2.7020963	AIC =324.88028
FLTPERC	2.77419090	0.68223792	4.06631010	SBC = 334.33938
UTILPERC	0.00415530	0.02377919	0.17474590	LL =-157.44014
SBPERC	0.00840450	0.03764517	0.22325520	SE =6.319328
CONSTANT	0.00946480	0.65388823	0.01447470	RASS =1,763.092
				RV = 38.933906
				MA =0

KEY:
AIC = Akaike Information Criterion
SBC = Schwartz Bayesian Criterion
LL = Log Likelihood
SE = Standard Error
RASS =Residuals Adjusted Sum of Squares
RV = Residual Variance
MA = Moving Average Parameter

The plot of the modelled sample of the series is shown in Figure 8.4. The 75 percent represents the first 33 observations of the series (i.e. the first 33 weekly observations of BDPERC). The plot shows a 'tight fit' within the 99 percent confidence limits tested for, within observation numbers 5, 10, 18 and 21 falling substantially out of the limits. An analysis of the fault occurring during these weeks indicate that the plant item was subjected to prolonged maintenance at these times probably due to the unavailability of spare parts.

Figure 8.4 - Fit Curve for CAT 446B(3) –Estimation Period Only



However, the test statistics indicate that the AIC and SBC were acceptable and the Box-Ljung statistic for the ACF function was also not statistically significant at any lag. Residual plots of ACF and PACF for the model are shown in Figures 8.5a and 8.5b respectively. As evidenced, they indicate no white noise and systematic trends. Rather the plots indicate a random distribution with a scatter of lags exceeding the confidence limits. R^2 value was 0.457 with a standard error estimate of 6.319.

Figure 8.5a – ACF Residuals for BDPERC for CAT 446B(3)

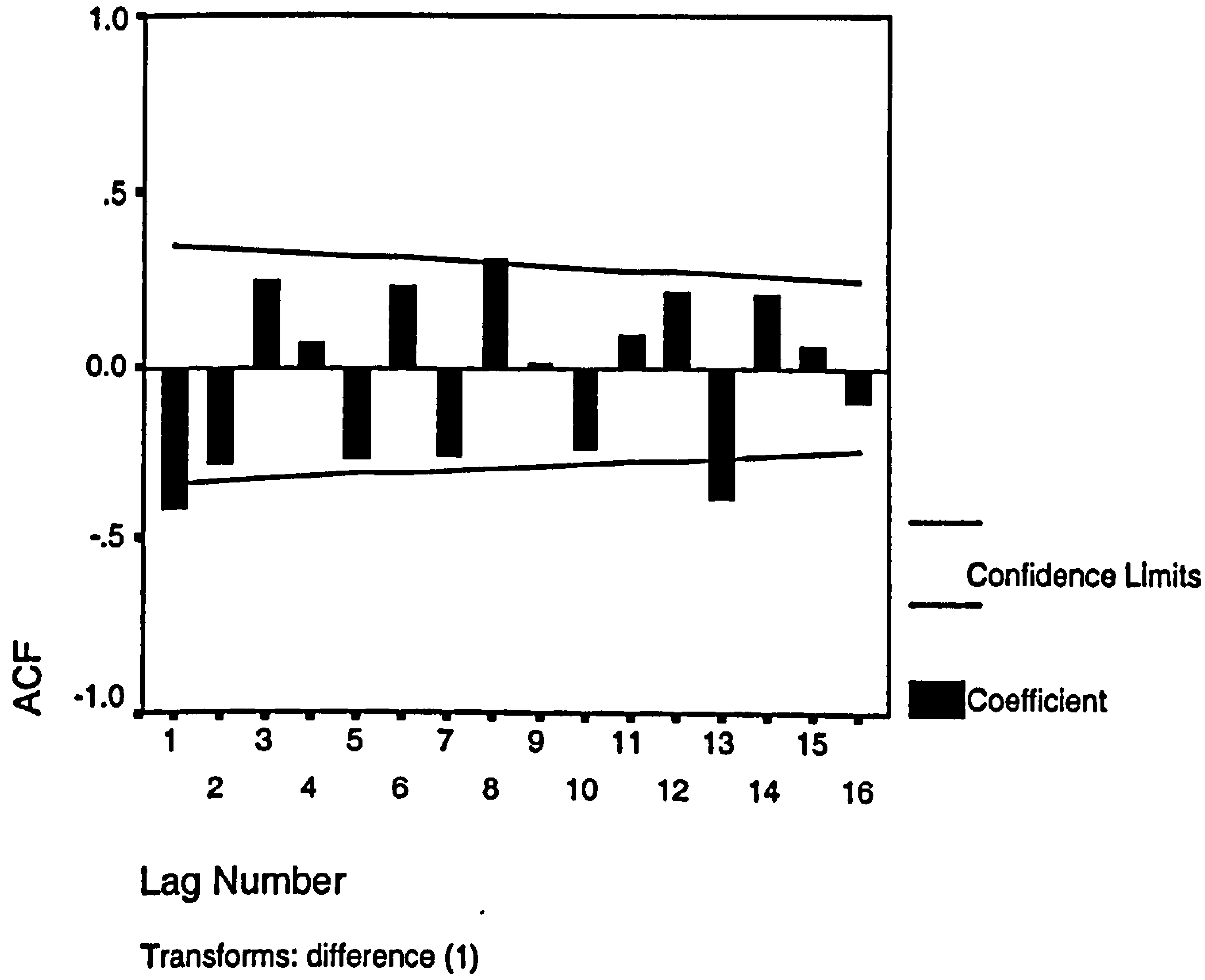
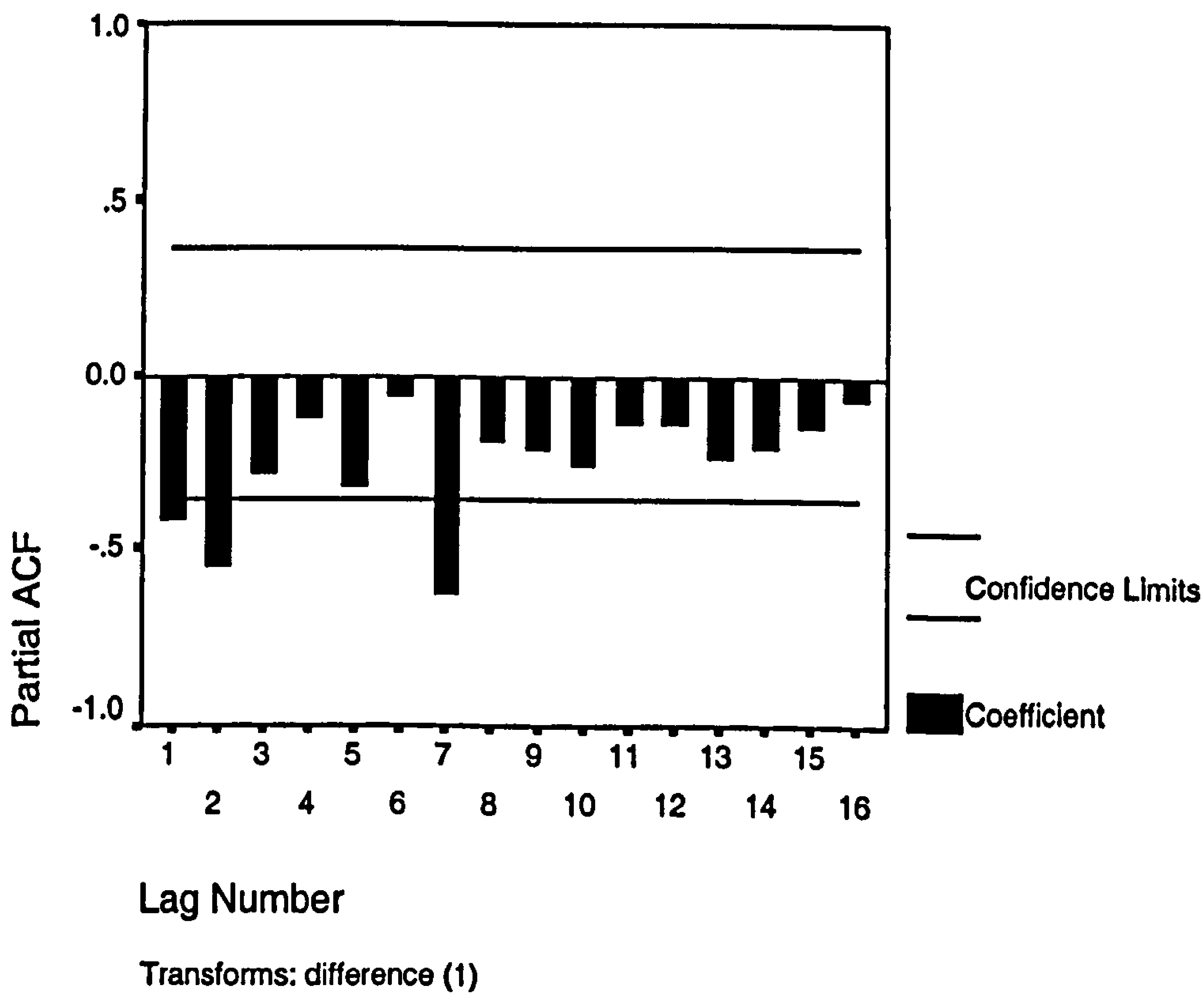
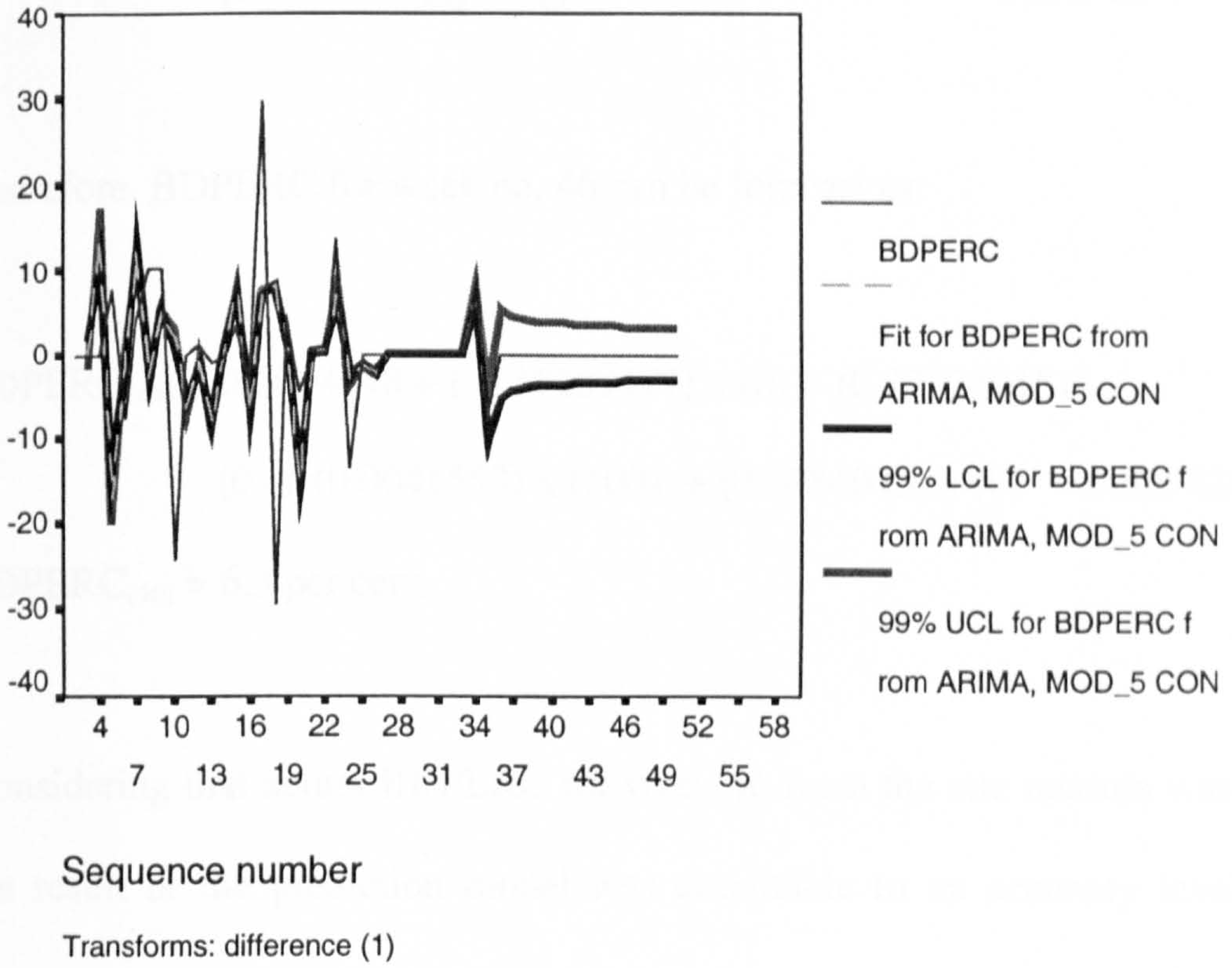


Figure 8.5b - ACF Residuals for BDPERC for CAT 446B(3)



A plot of the fit curve for the model during the post-estimation period (i.e. inclusive of the held-out sample) is shown in Figure 8.6. This is for the purposes of validating the accuracy of the model and observing its behaviour within the 99 percent confidence interval.

Figure 8.6 - Fit Curve for CAT 446B(3) – Estimation and Validation Periods



As observed in the fit curve of figure 8.6, the model provides a very suitable estimation of BDPERC during the forecasting period. Based on this result, the ARIMA (1,1,0) model may be accepted as a good predictor of BDPERC for backhoe loaders. Values of the parameters are (from Table 8.1): AR (1) = -0.3922127; FLTPERC = 2.7741909; UTILPERC = 0.0041553; SBPERC = 0.0084045; Constant = 0.0094648; and e_t = 6.319328.

Based on equation 6.1, the model can therefore be represented for the backhoe loader as:

$$BDPERC_{(t)} = CONSTANT + (-0.39189477) \times BDPERC_{(t-1)} + (0.277260181) \times (FLTPERC)_{(t-1)} + (0.0041553) \times (UTILPERC)_{(t-1)} + (0.0084045) \times (SBPERC)_{(t-1)} + e_{(t)} \qquad \text{.........................(8.1)}$$

Therefore, BDPERC for week no. 46 can be forecast as:

$$BDPERC_{(46)} = 0.0094648 + (-0.39189477) \times (0) + (0.277260181) \times (0) + (0.0041553) \times (100) + (0.0084045) \times (0) + 6.319328$$

$$BDPERC_{(46)} = 6.3 \text{ per cent}$$

Considering that actual BDPERC for week 46 from the site records was 8.1 percent, the result of the prediction model was acceptable to an accuracy level of over 75 percent.

Hydraulic Excavator Predictor Model

The CAT 311B(2) model was selected as specific case study for the excavator breakdown prediction model. This selection was based on the results of the descriptive analysis conducted on the historical data of the hydraulic excavators investigated as part of the research (Chapter 6).

As it was in the case of the wheel loader and backhoe loader models, plots of the sequence charts for BDPERC against time (in weeks) for the historical data revealed non-stationarity and non-seasonality. However, stationarity of the series was again achieved after a first order differencing, particularly after the fourth observation of the sequence. These are shown in Figures 8.7a and 8.7b for the CAT 311B(2) hydraulic excavator.

Figure 8.7a – Sequence Plot for CAT 311B(2) Backhoe-Loader (Original Data)

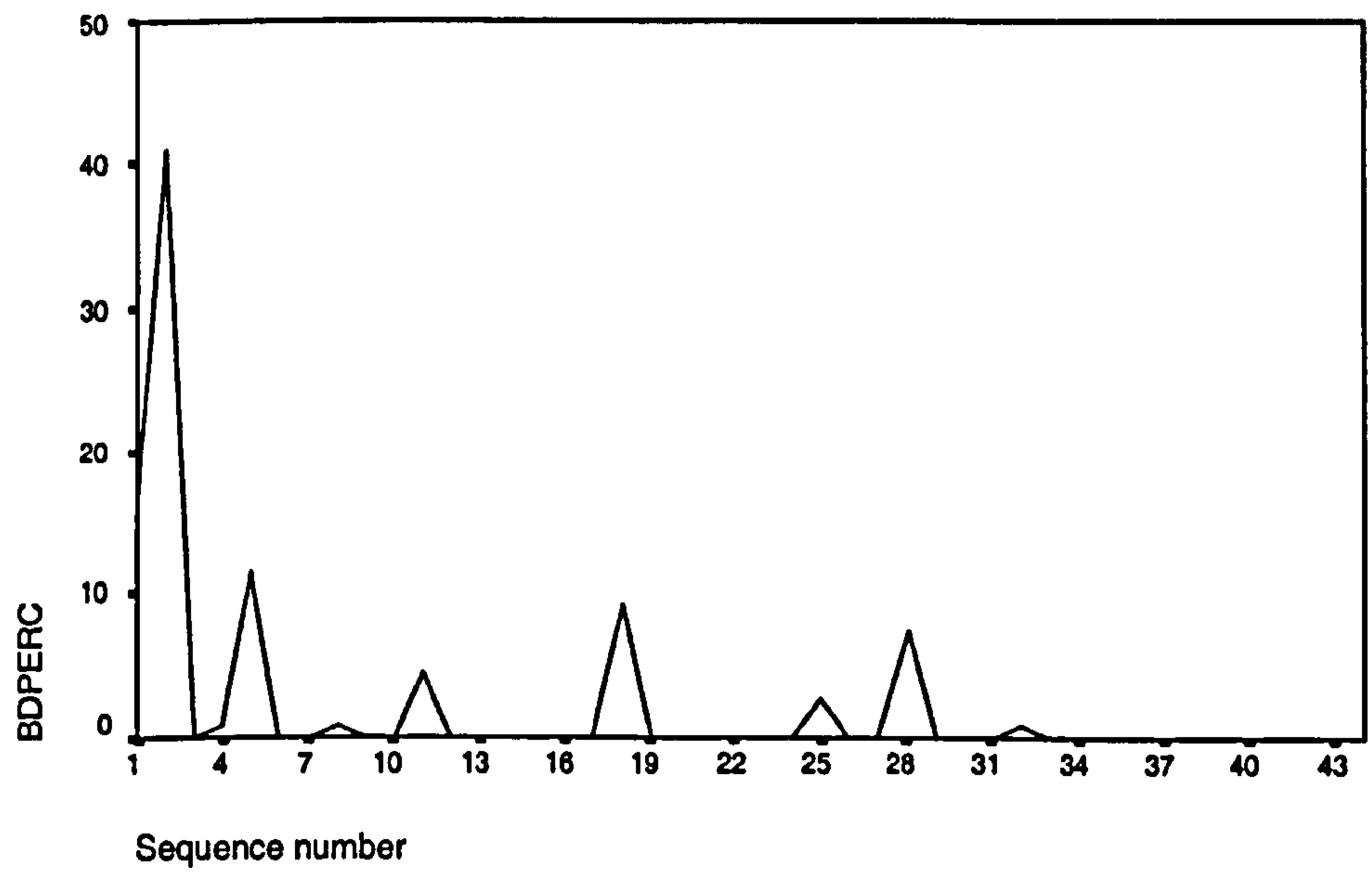
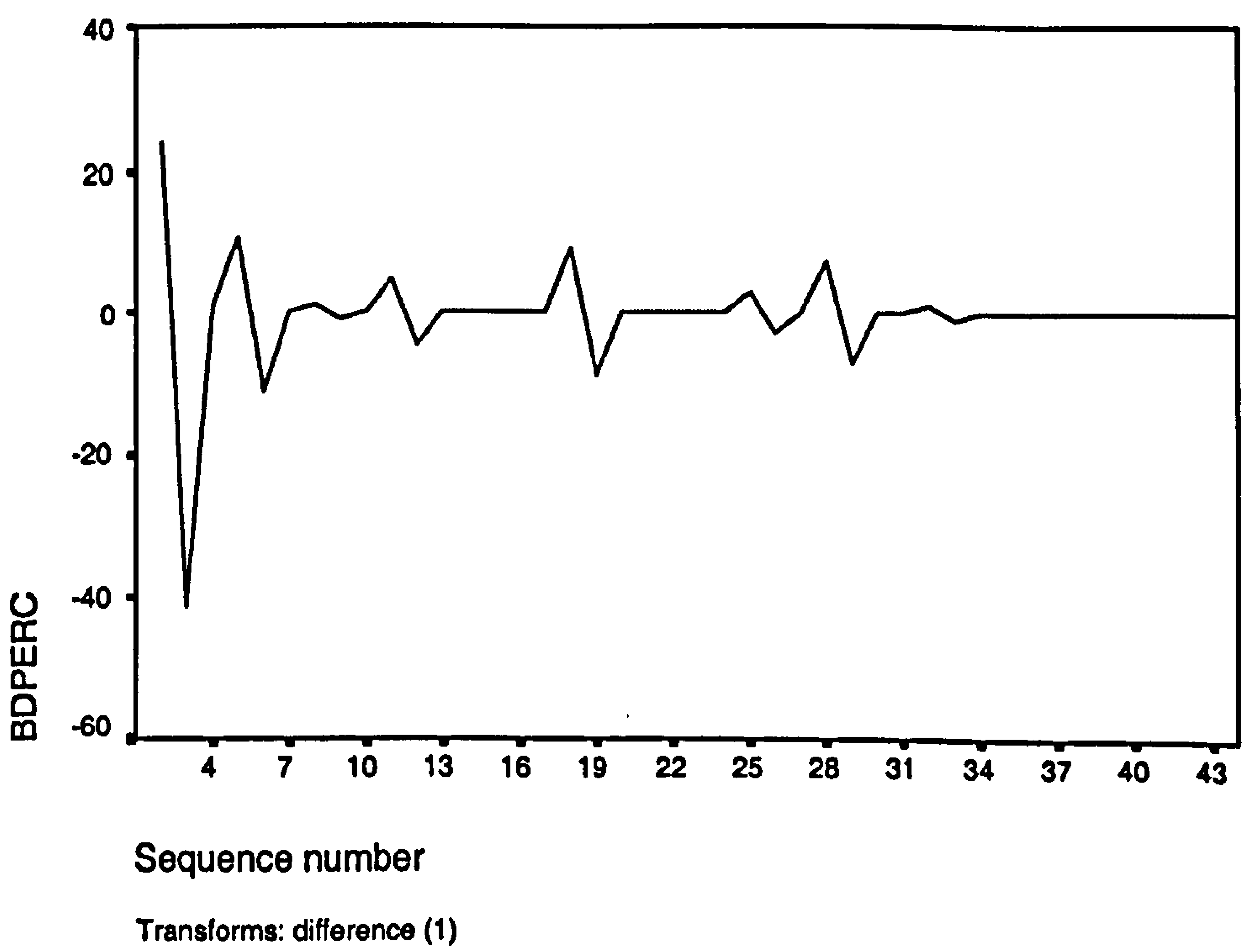
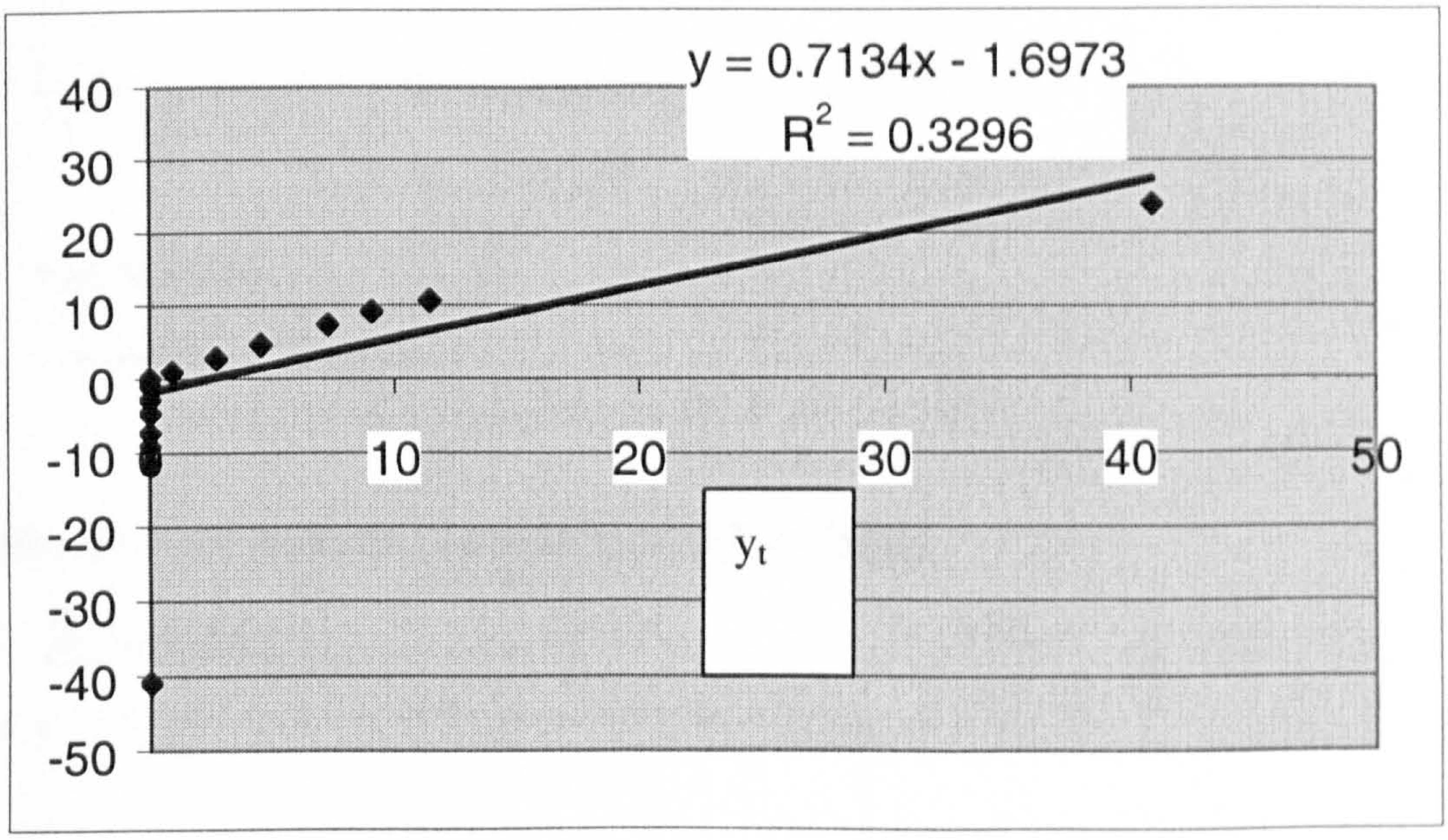


Figure 8.7b – Sequence Plot for CAT 311B(2) Backhoe-Loader (Transformed)



Results of the Dickey-Fuller test also confirmed the stationarity of the series (refer to Figure 8.8). The regression yielded an estimated slope coefficient of 0.7134 and a t-statistic of –1.6973, which exceed the critical values at 2%, 5% and 10%. These values are –4.15, -3.80 and –3.18 respectively for an AR model with constant based on 50 observations. This confirmation indicates an I(1) ARIMA model (i.e. d=1).

Figure 8.8: Regression results of Δyt on yt for CAT 311B(2)



The plots of autocorrelation and partial autocorrelation for the series were examined in order to determine p and q for the AR and MA components of the model respectively. Figures 8.9a and 8.9b show these plots as obtained for the BDPERC series of the CAT 311B (2) model. Although two significant first spikes were observed in the PACF plot, the first significant spike in the ACF plot substantially indicates that p = 1. The results indicate that the series represent an AR (1) model.

Figure 8.9a: Plots of Autocorrelation for CAT 311B(2)

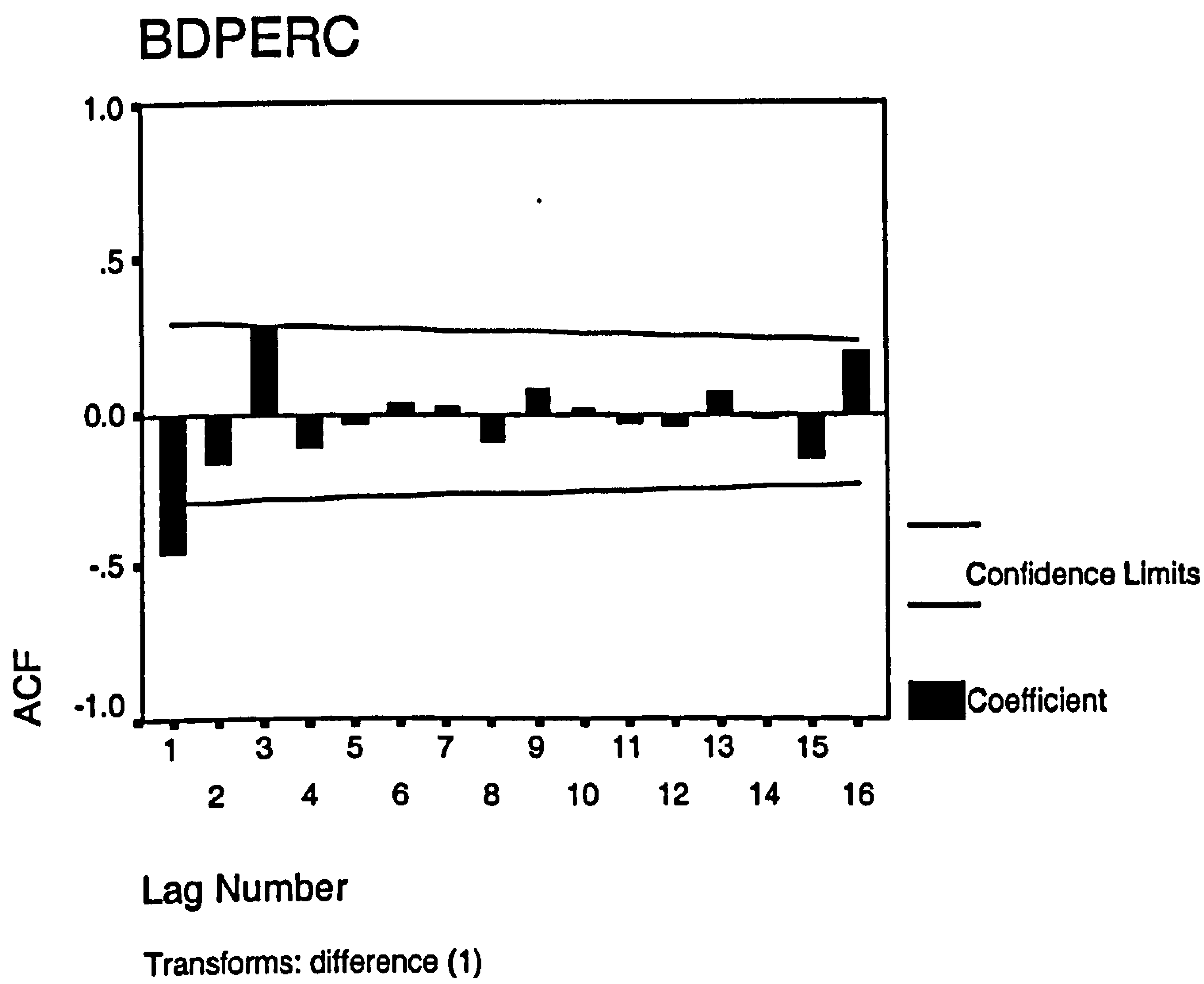


Figure 8.9b: Plots of Autocorrelation for CAT 311B(2)

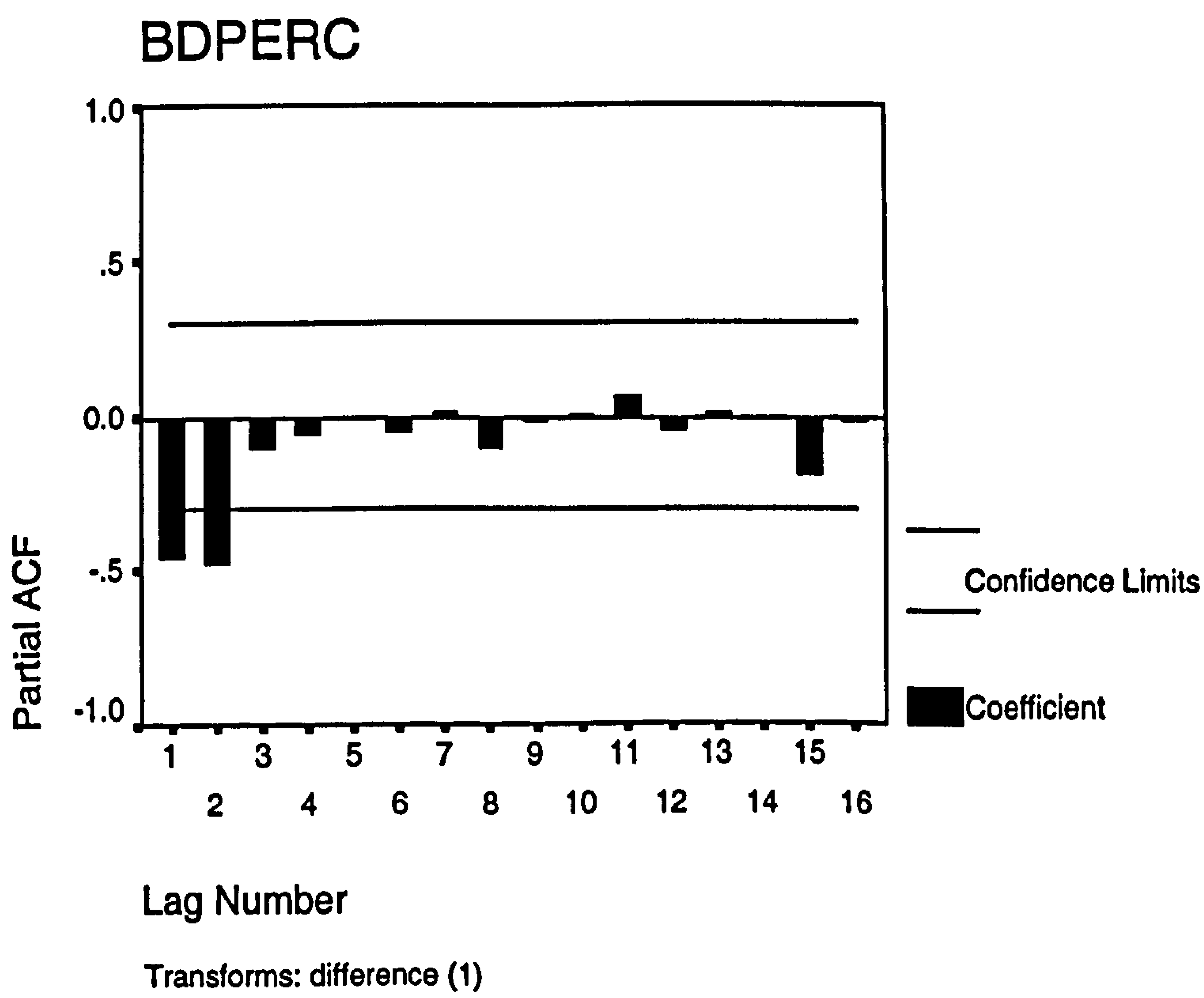


Table 8.2- ARIMA Statistics for the CAT 311B(2)

Variable	Beta	Standardised Beta	T- Ratio	Statistics
BDPERC (AR1)	-0.55324591	0.13618394	-4.06249020	AIC =294.25109
FLTPERC	0.72769287	0.66506099	1.09417460	SBC = 303.0579
UTILPERC	-0.07878984	0.04860456	-1.6210380	LL =-142.12595
SBPERC	-0.02367837	0.03223664	-0.7345172	SE =0.6935187
CONSTANT	0.65681235	0.69591600	0.9438098	RASS =1,858.367
				RV = 48.490592
				MA =0

KEY:
AIC = Akaike Information Criterion
SBC = Schwartz Bayesian Criterion
LL = Log Likelihood
SE = Standard Error
RASS =Residuals Adjusted Sum of Squares
RV = Residual Variance
MA = Moving Average Parameter

Modelling the series within a 75 per cent estimation period (first 30 observations) revealed the results shown in Figure 8.10. The series shows a significant deviation from the fit curve during the first five observations. However, after these 'shocks' the series was observed to significantly conform to the fit curve within the 95% upper and lower limit confidence intervals.

AIC and SBC test statistics were suitable and the R^2 value and standard error estimates were 0.3296 and 0.6935 respectively. Furthermore, the residual plots of the ACF and PACF indicate random distribution with no specific trends and/or white noise at most lags (Figures 8.11a and 8.11b).

The result of testing the model during the validation period is shown in Figure 8.12. The fit curve shows that the model reasonably predicts the values of BDPERC within the validation period. Therefore, the model should be suitable for BDPERC prediction for hydraulic excavators.

Figure 8.10 - Fit Curve for CAT 311B(2) –Estimation Period Only

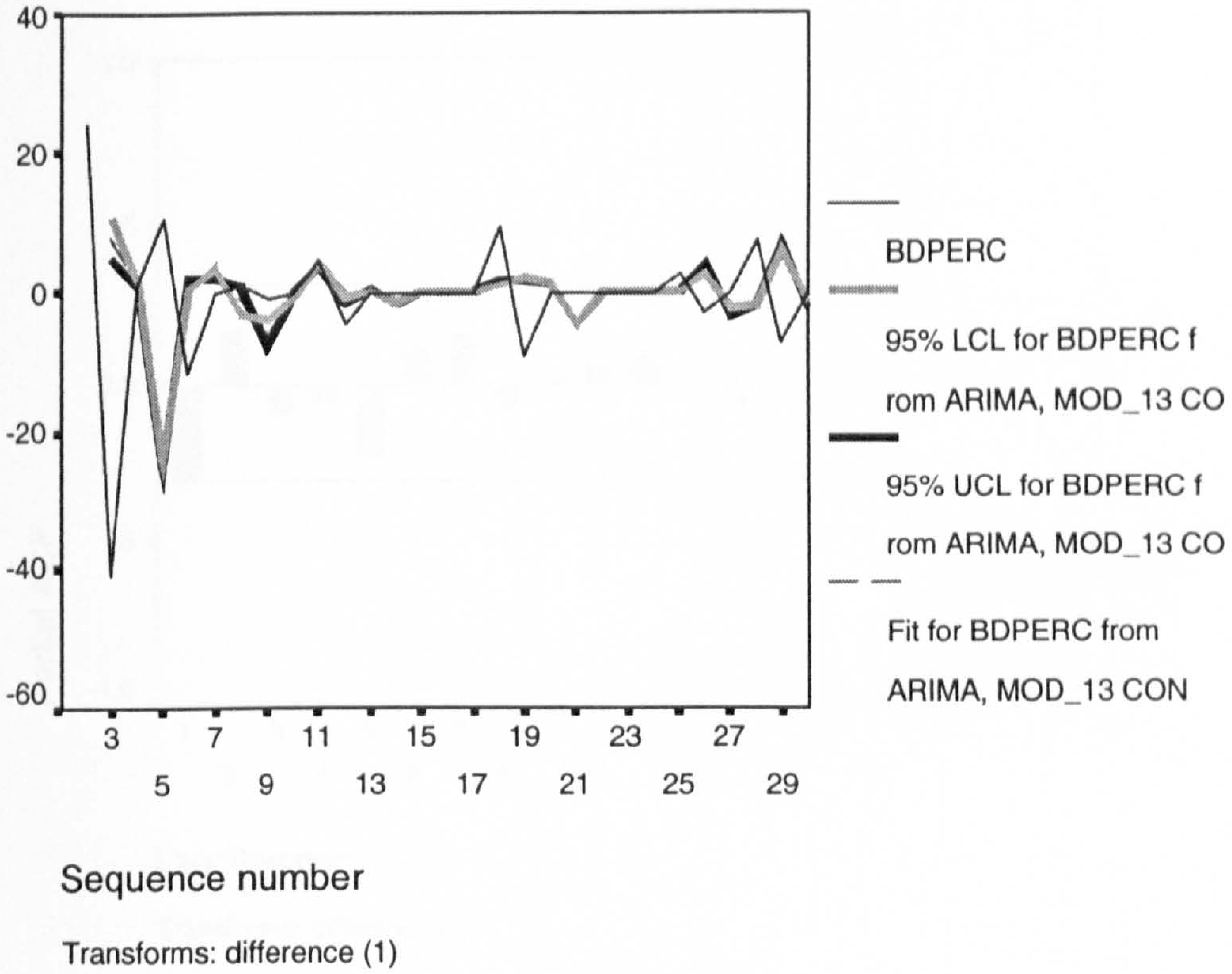


Figure 8.11a – ACF Residuals for BDPERC for CAT 311B(2)

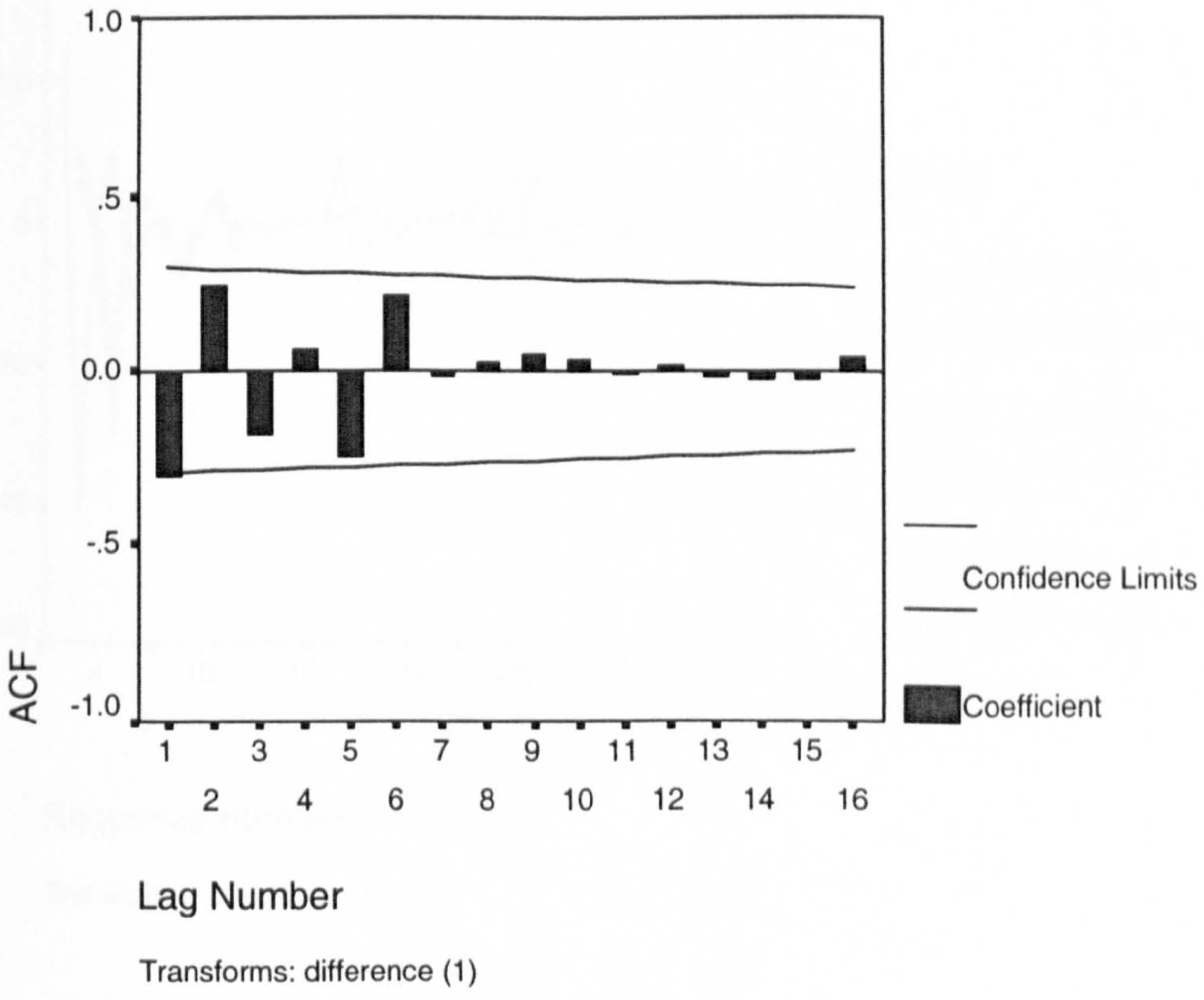


Figure 8.11b – PACF Residuals for BDPERC for CAT 311B(2)

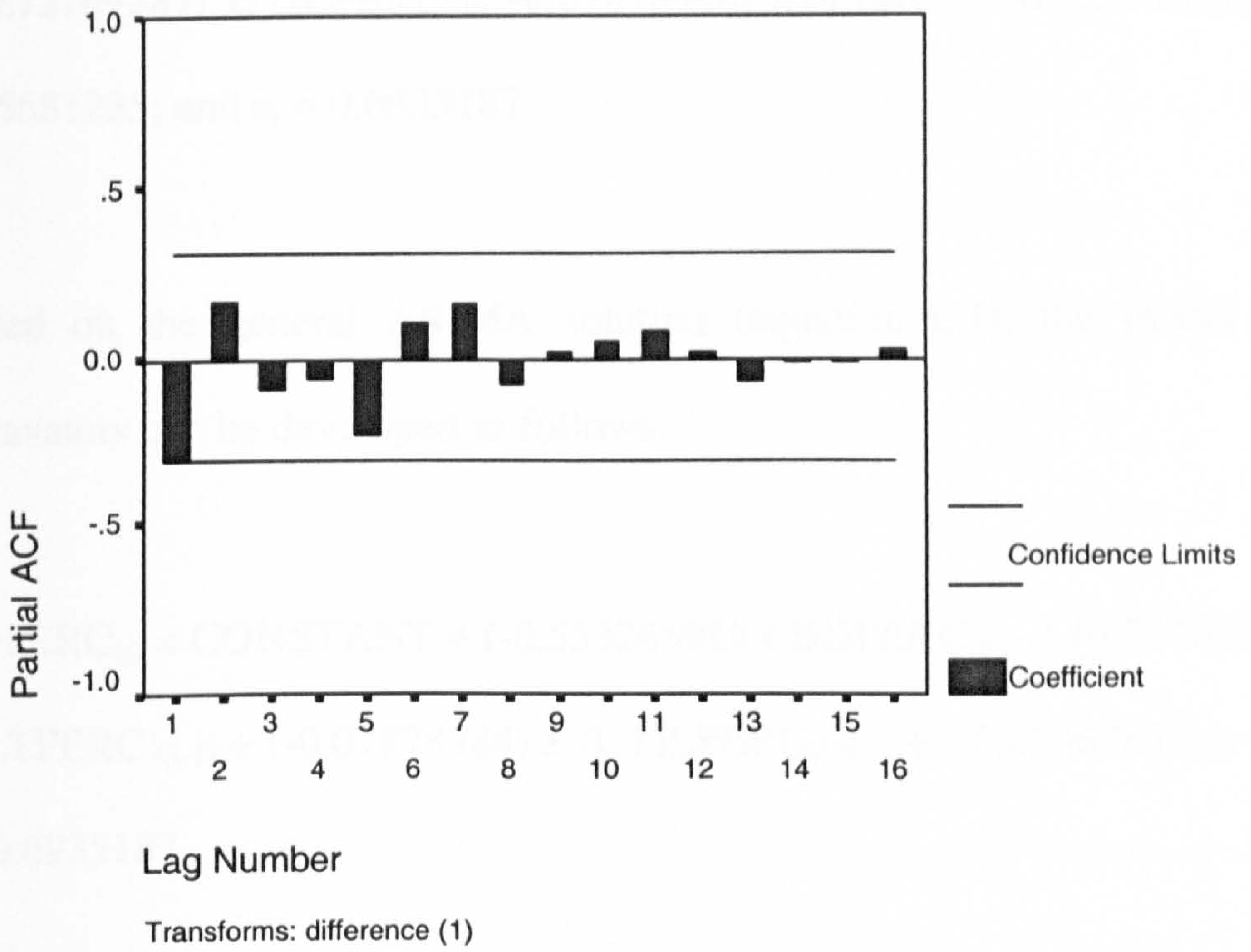
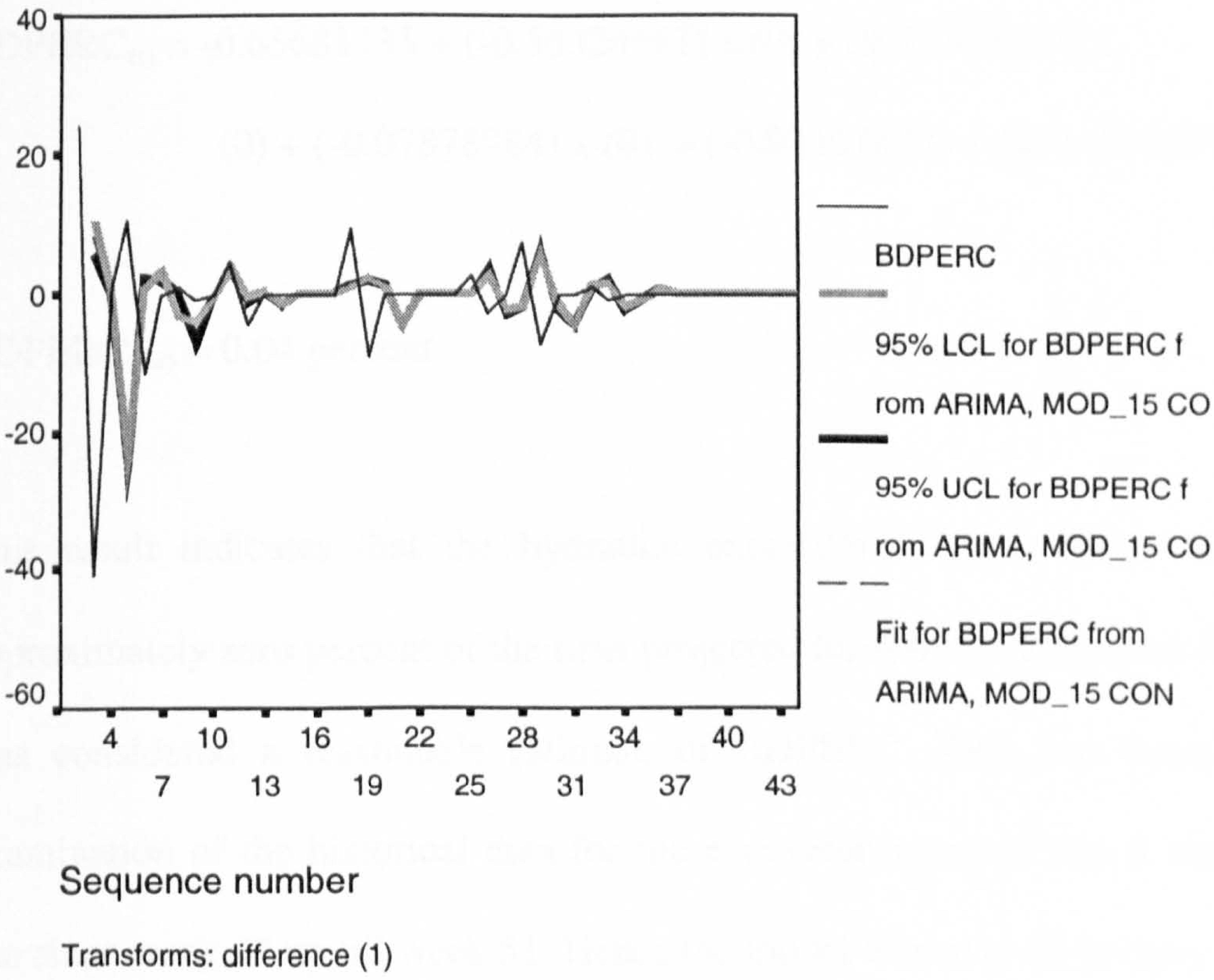


Figure 8.12 - Fit Curve for CAT 311B(2) –Estimation and Validation Periods



Values of the parameters (from table 8.2) include: AR (1) = -0.55324591; FLTPERC = 0.72769287; UTILPERC = -0.07878984; SBPERC = -0.02367837; Constant = -0.65681235; and e_t = 0.6935187.

Based on the general ARIMA solution (equation 6.1), the model for hydraulic excavators can be developed as follows;

$$BDPERC_{(t)} = CONSTANT + (-0.55324591) \times BDPERC_{(t-1)} + (0.72769287) \times (FLTPERC)_{(t-1)} + (-0.07878984) \times (UTILPERC)_{(t-1)} + (-0.02367837) \times (SBPERC)_{(t-1)} + 0.6935187 \qquad \text{.........................(8.2)}$$

Therefore, BDPERC for week no. 52 can be forecast as:

$$BDPERC_{(t)} = -0.65681235 + (-0.55324591) \times (0) + (0.72769287) \times (0) + (-0.07878984) \times (0) + (-0.02367837) \times (0) + 0.6935187$$

$BDPERC_{(52)}$ = 0.04 percent

This result indicates that the hydraulic excavator is expected to breakdown for approximately zero percent of the time projected for it to work in week 46. This result was considered a reasonable estimate of BDPERC. This was because a critical examination of the historical data for the excavator revealed that it had been out of use since week 40 up till week 51. Hence the model was over 95 percent accurate.

Off Highway Hauler Predictor Model

Out of the five off highway haulers investigated, the utilisation and breakdown history data set of the CAT 777D (5) was selected for the model development process for off-highway plant. This choice was also based on the outcome of the descriptive analysis/historical data synthesis conducted on the historical data of the plant items (Chapter 6).

As with the other plant types, similar dependent and independent variables were modelled. The model also considered the lagged BDPERC an endogenous independent variable. Establishing the stationarity and seasonality of the series requires that the sequence chart of the BDPERC for the off highway hauler is plotted against time (in weeks). As evidenced in Figure 8.12a, the series is non-stationary and non-seasonal and therefore required transformation by differencing. The outcome of the transformation process is given in Figure 8.12b.

Confirmatory Dickey-Fuller tests also assisted in proving the stationarity of the series. The tests showed that the null hypothesis that $\alpha_1 = 0$ cannot be rejected. The results of the regression (Figure 8.13) gave an estimated slope of 0.9638 and a t-statistic of –3.0332, which are satisfactory results for the test (based on the critical values of table 7.2). Hence the series is confirmed an ARIMA, I (1) model.

Figure 8.12a – Sequence Plot for CAT 777D(5) Off-Highway Hauler (Original Data)

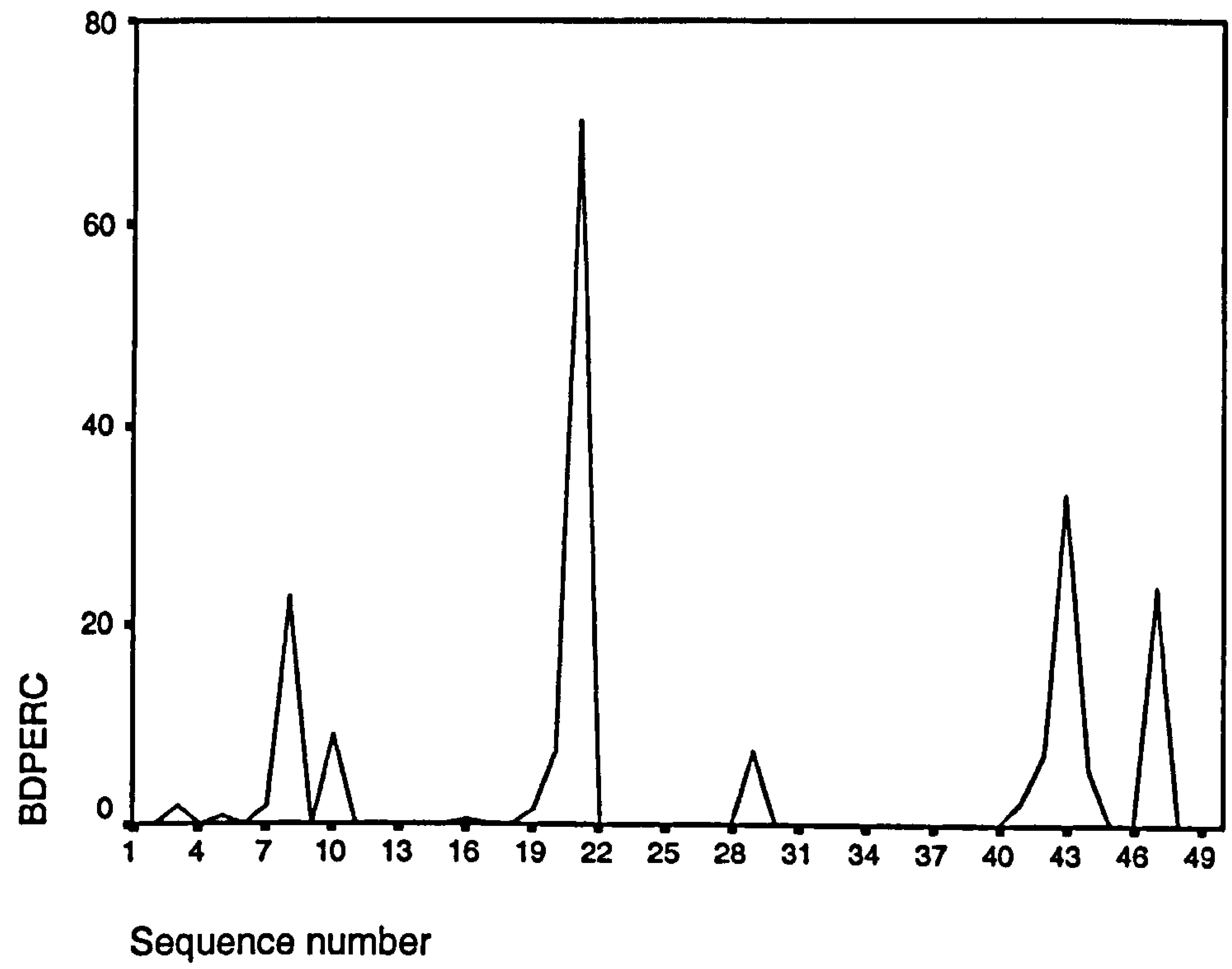


Figure 8.12b – Sequence Plot for CAT 777D(5) Off-Highway Hauler (Transformed)

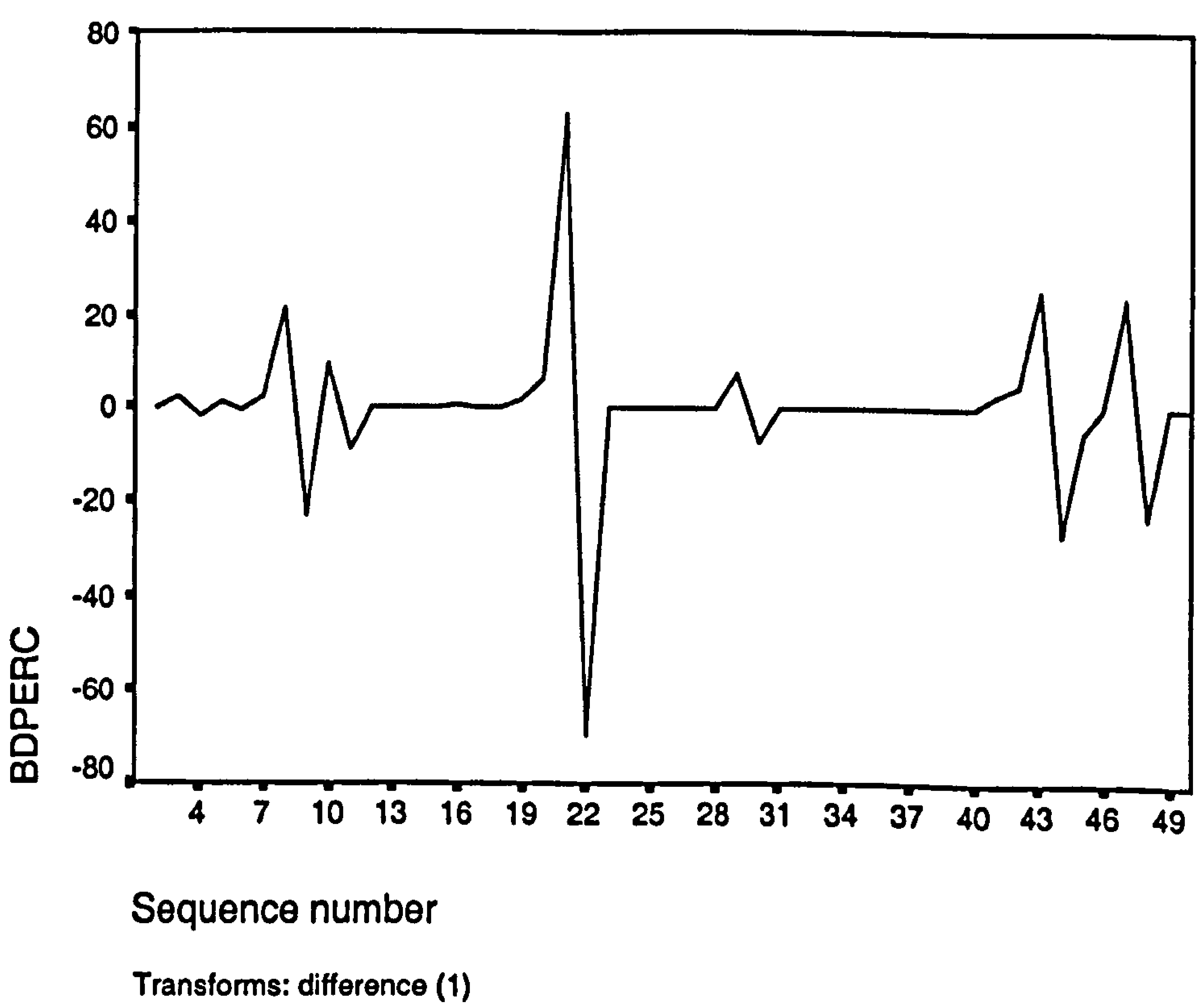
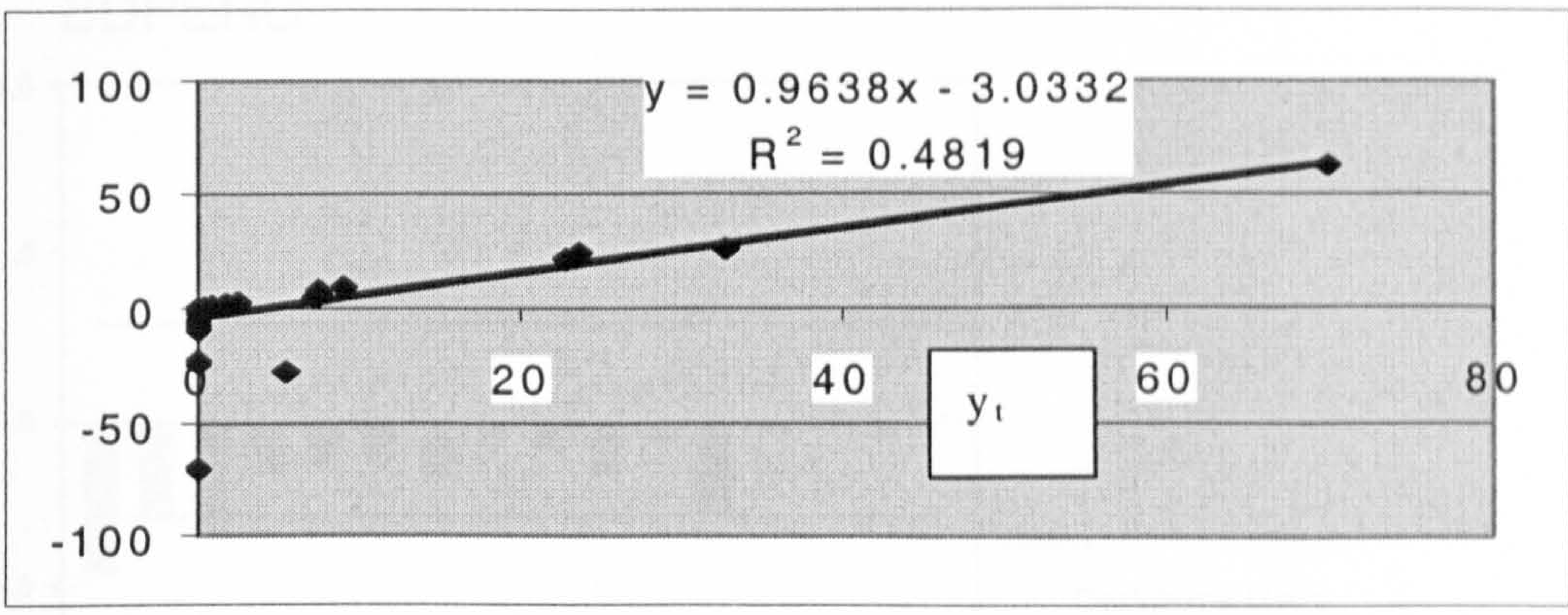


Figure 8.13: Regression results of Δyt on yt for CAT 777D(5)



The determination of the other parameters for the ARIMA model, i.e. p and q for autoregressive and moving average respectively entailed a plot of the autocorrelation and partial autocorrelation of the series. Both plots indicate that the series could be characterised as an ARIMA AR(1) model. Also since the values of the ACF were alternating and the PACF indicated declining values at progressive lag, the series could also be diagnosed as an MA (0) ARIMA series (refer to Figures 8.14a and 8.14b).

Figure 8.14a: Plots of Autocorrelation for CAT 777D(5)

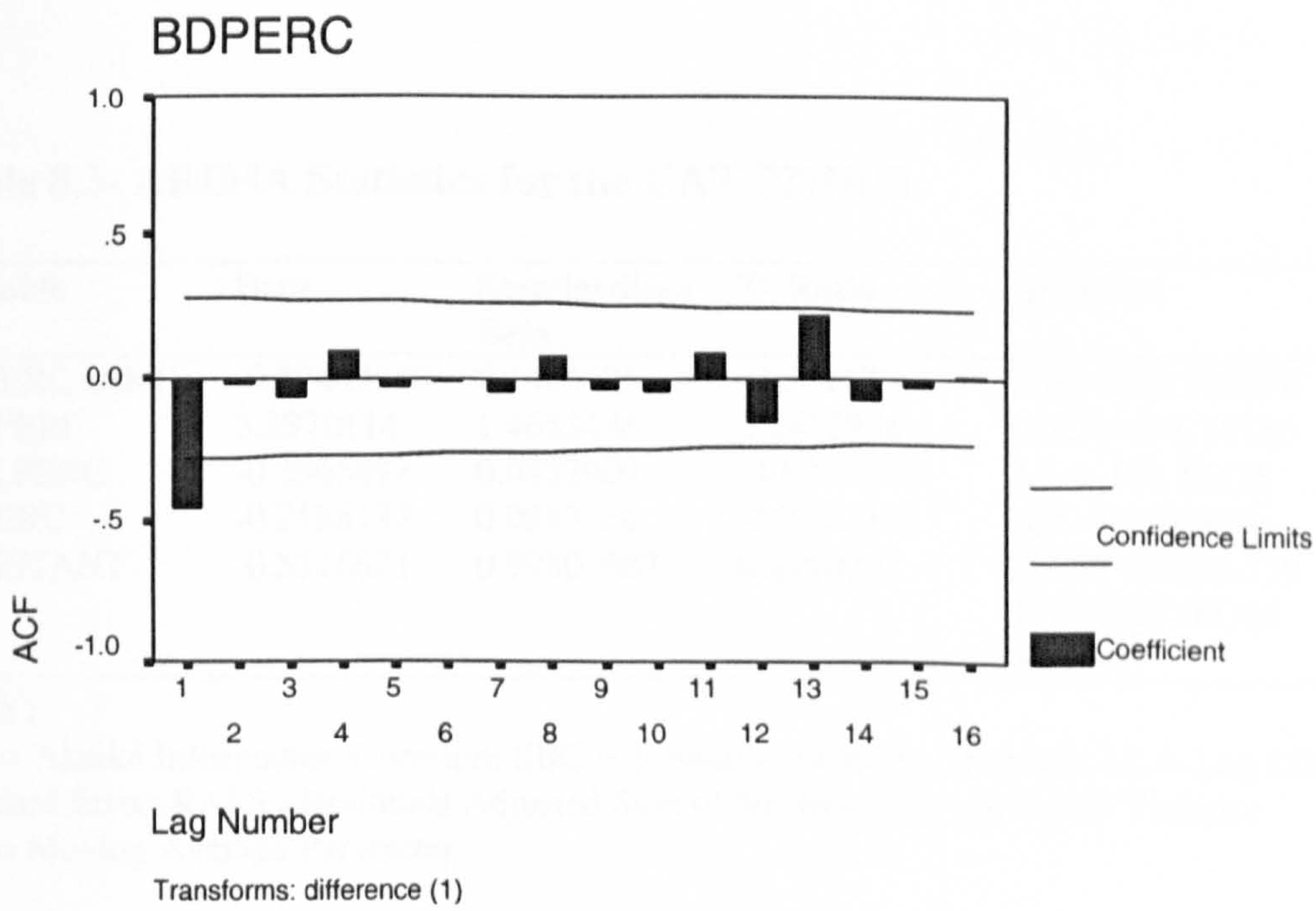
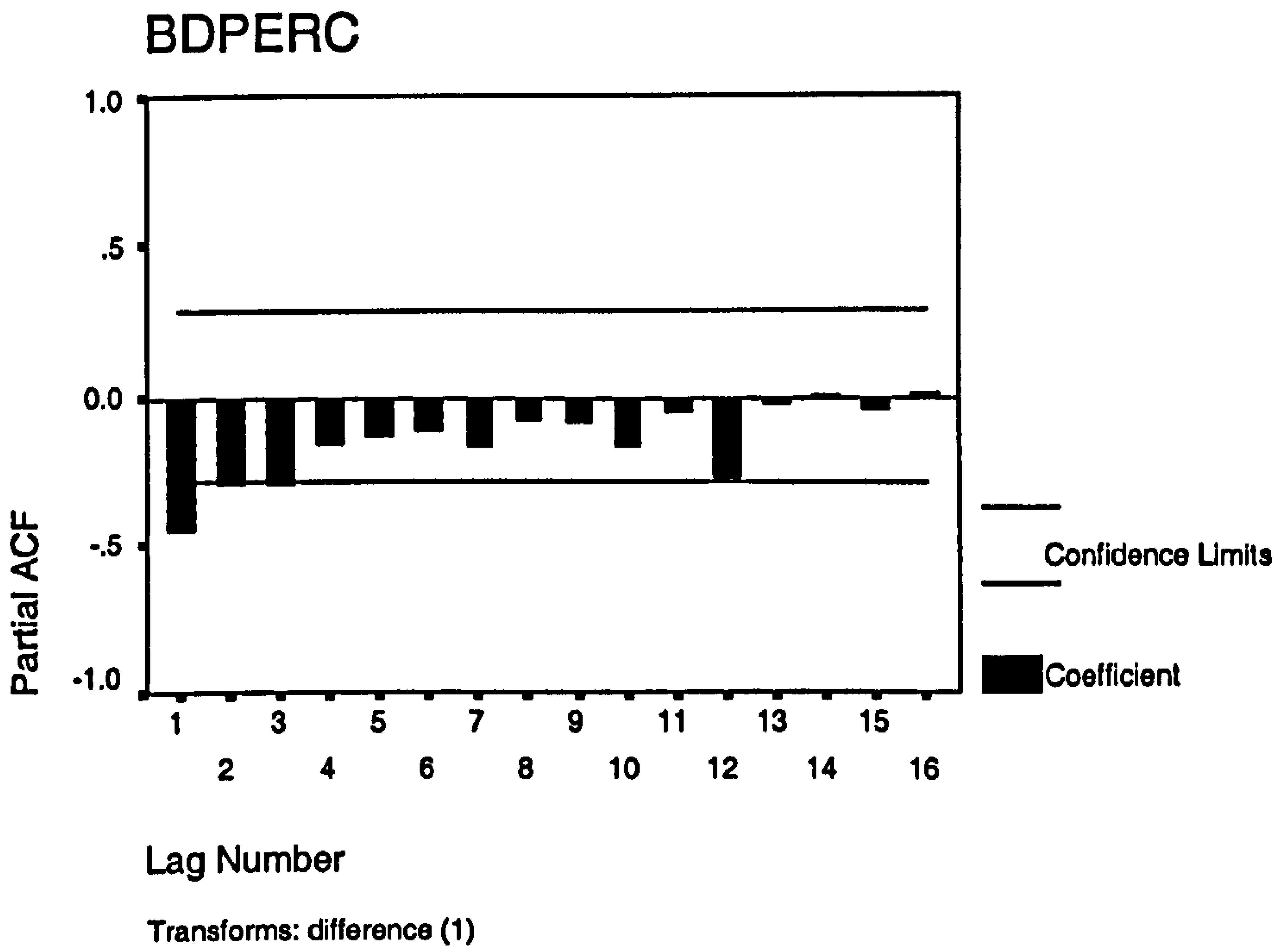


Figure 8.14b: Plots of Partial Autocorrelation for CAT 777D(5)



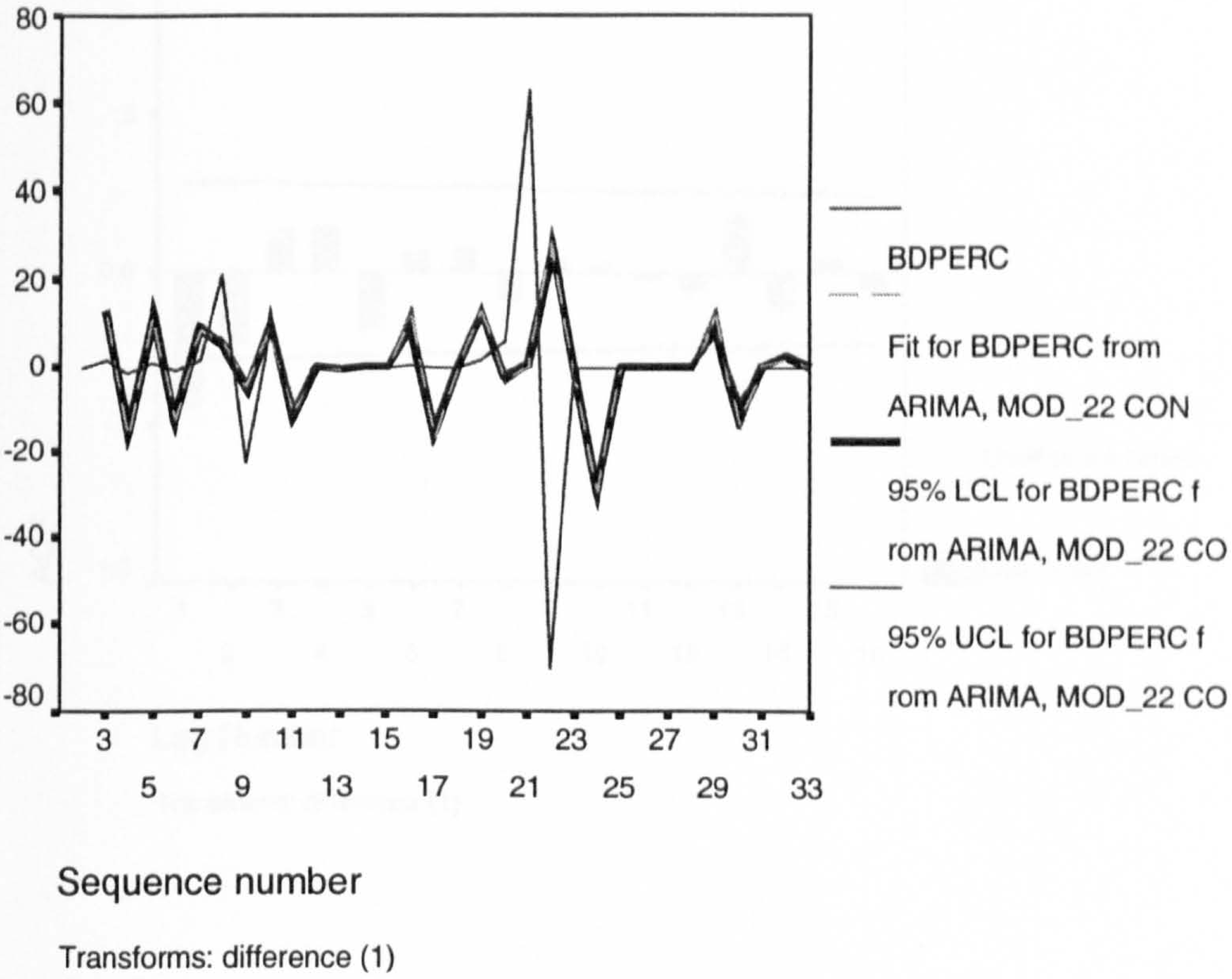
Analysing the ARIMA (1,1,0) model using the SPSS Trends software produced the fit statistics and the ARIMA coefficients for the off-highway BDPERC prediction model. The result of the modelling of the series within an estimation period of 33 observations is shown in Table 8.3, while the fit curve (for this estimation period) is displayed in Figure 8.15.

Table 8.3- ARIMA Statistics for the CAT 777D(5)

Variable	Beta	Standardised Beta	T- Ratio	Statistics
BDPERC (AR1)	-0.37442660	0.1460225	-2.5641708	AIC =382.322276
FLTPERC	3.2970114	1.4683446	2.2453936	SBC = 391.78186
UTILPERC	-0.3966897	0.0822909	-4.8205770	LL =-186.16138
SBPERC	-0.2188132	0.0983736	-2.2243075	SE =1.1357832
CONSTANT	-0.5316621	0.99807987	0.4460293	RASS =5,693.539
				RV = 129.00034
				MA =0

KEY:
AIC = Akaike Information Criterion; SBC = Schwartz Bayesian Criterion; LL = Log Likelihood; SE = Standard Error; RASS =Residuals Adjusted Sum of Squares; RV = Residual Variance
MA = Moving Average Parameter

Figure 8.15 - Fit Curve for CAT 777D(5) –Estimation Period Only



The fit curve shows that the model predicts series adequately although a few of the observations (mostly the first nine) fell out of the 95 percent upper and lower confidence intervals. The test statistics also indicate good AIC and SBC statistics. The residual plots of ACF and PACF for the model are shown in Figures 8.16a and 8.16b respectively – the significant first spike of Figure 8.16a indicating AR (1). Similarly, R^2 value was 0.4819 and a standard error estimate of 1.135. A plot of the fit curve inclusive of the validation period is shown in figure 8.17. The curve again shows the accuracy of the model in predicting BDPERC.

Figure 8.16a – ACF Residuals for BDPERC for CAT 777D(5)

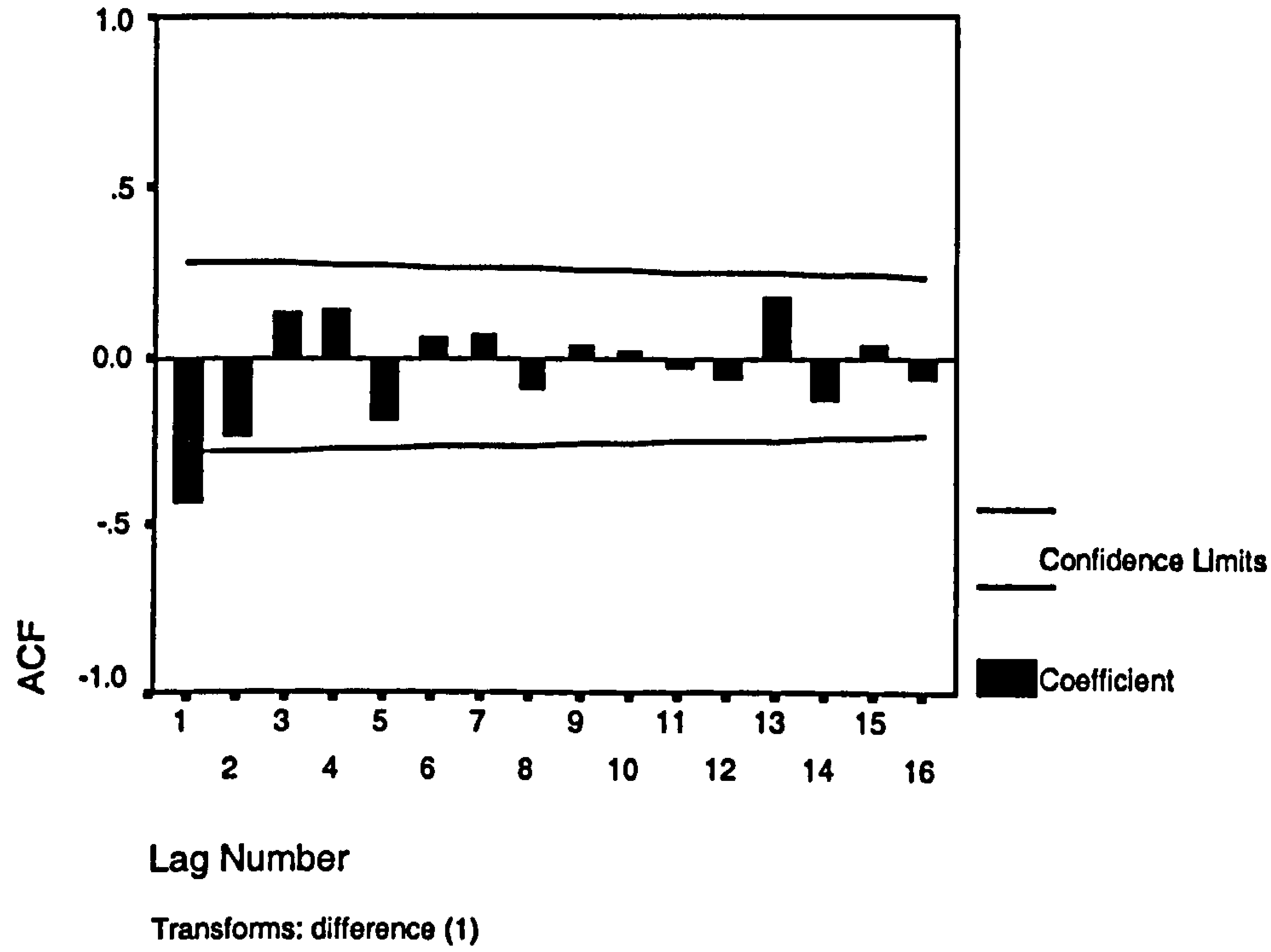


Figure 8.16b – PACF Residuals for BDPERC for CAT 775D(5)

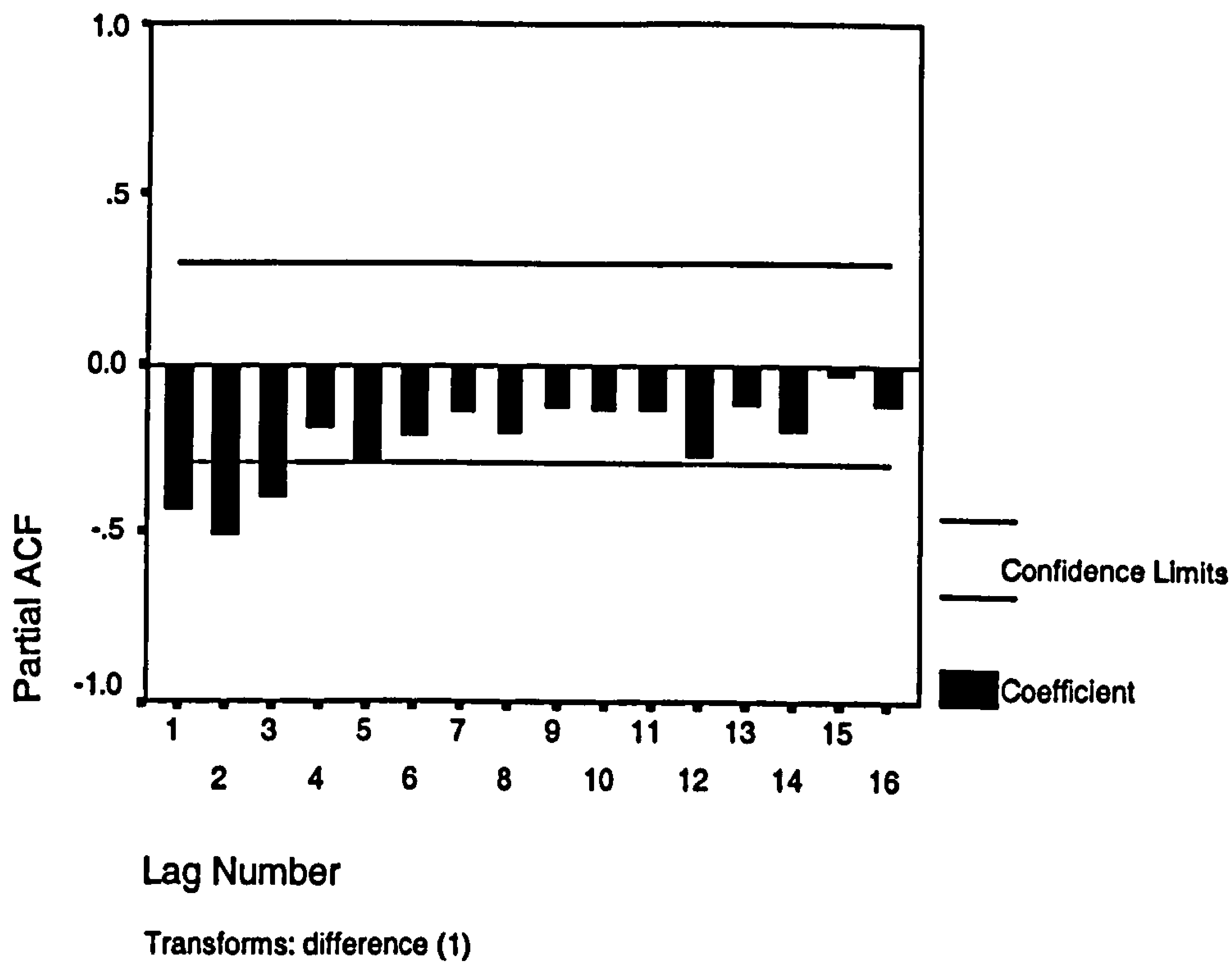
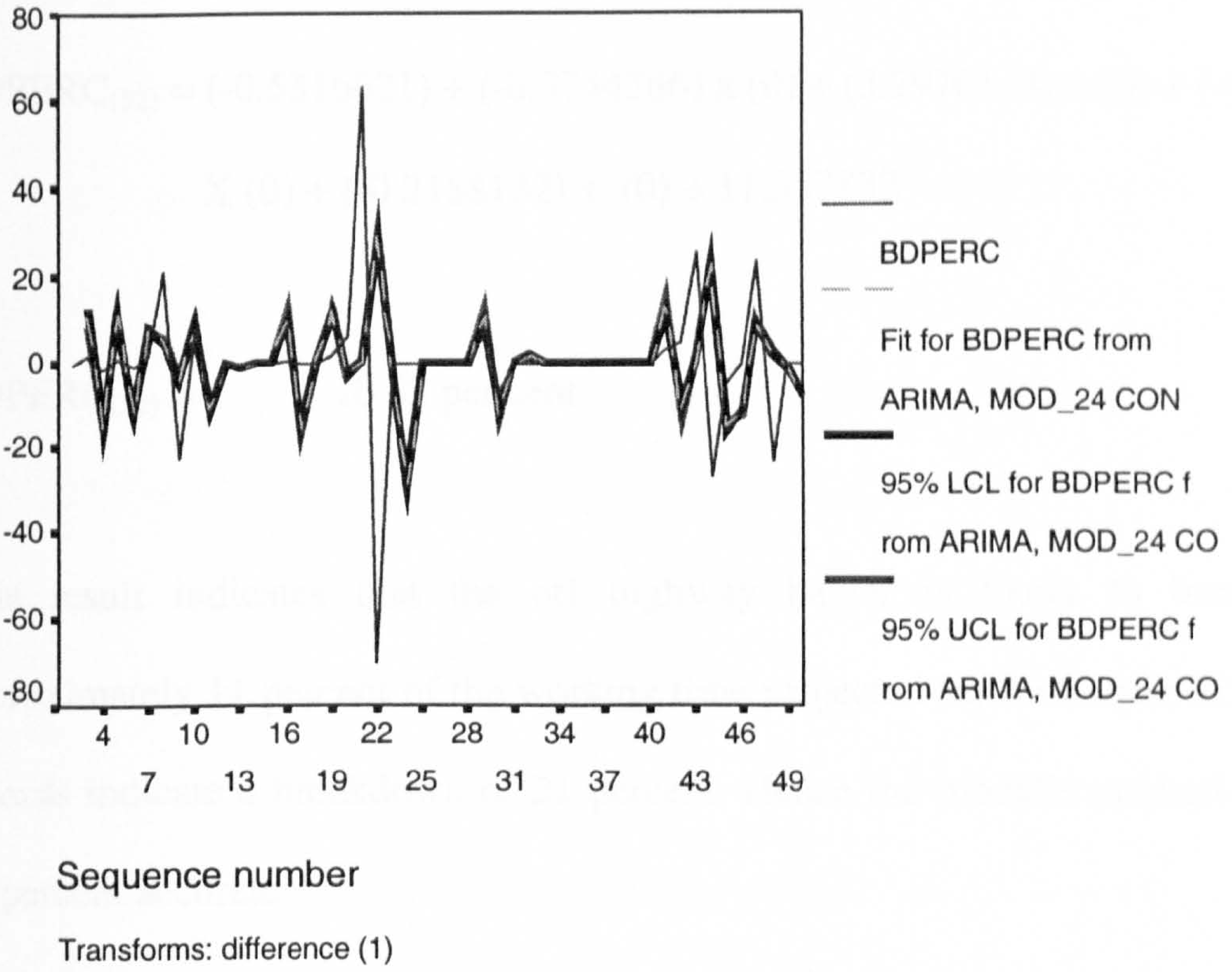


Figure 8.17 - Fit Curve for CAT 777(5) – Estimation and Validation Periods



The ARIMA model for BDPERC can therefore be constructed for off-highway loaders (with reference to the ARIMA general equation 6.1) as follows:

$BDPERC_{(t)}$ = CONSTANT + (-0.3744266) x $BDPERC_{(t-1)}$ + (3.2970114) x $(FLTPERC)_{(t-1)}$ + (-03966897) x $(UTILPERC)_{(t-1)}$ + (-0.2188132) x $(SBPERC)_{(t-1)}$ + 1.1357832 ……………………..(8.3)

i.e. using the values obtained from the analysis: AR(1) = -0.3744266; FLTPERC = 3.2970114; UTILPERC = -0.3966897; SBPERC = -0.2188132; Constant = -0.5316621; and e_t = 1.1357832.

Hence,

$$BDPERC_{(52)} = (-0.5316621) + (-0.3744266) \times (0) + (3.2970114) \times (0) + (-0.3966897) \times (0) + (-0.2188132) \times (0) + 11.357832$$

$$BDPERC_{(52)} = 10.82 \text{ per cent.}$$

This result indicates that the off highway hauler is likely to breakdown for approximately 11 percent of the working time projected for it in week 52. Actual site records indicate a breakdown of 21 percent. Hence the model's prediction was over 52 percent accurate.

This model is the fourth of the time series models developed for predicting plant breakdown time as a percentage of hours worked by different plant items. The analysis conducted revealed that the models appeared to be suitable for the intended purposes. This assertion was based on the observed shapes of the BDPERC fit curves when matched with the corresponding actual curves of BDPERC obtained from field investigations. Also, using the 75 percent estimation period in each case and simulating the predictive capabilities of the models during a 'forecast period' enabled a fair assessment of the model's capabilities. In all cases, the 'match' between actual and predicted values were very suitable. However, in order to ascertain robustness of the models and quantify their degrees of accuracies, a validation procedure based on the determination of the models' statistical performance measures was conducted. Details of these are herby discussed as follows.

VALIDATION OF MODELS – Performance Statistics

Various methods exist for validating the accuracy of time series models. These include; Root Mean Square Error (RMSE), Mean Absolute Deviation (MAD), Mean Percentage Error (MPE), Mean Absolute Error (MAE) and other similar techniques (Ruddock, 1995; Chatfield, 1996; Edwards and Holt, 2001; Edwards et al, 2001). Since all the models developed for the wheel loader, hydraulic excavator, backhoe loader and off-highway hauler plant types were based on the ARIMA (1,1,0) model, the validation procedure utilised was the same for all models.

The MAD and the RMSE calculations were conducted in order to test the statistical forecasting accuracy of the derived ARIMA models. Also, the Analysis of Variance (ANOVA) technique was used to facilitate a procedure of testing the statistical significance of the combined variables: the lagged BDPERC, FLTPERC, UTILPERC and SBPERC on the predicted results.

The formulas for the MAD and RMSE are:

$$MAD = \frac{\sum |Y - F|}{n} \tag{8.4}$$

$$RMSE = \sqrt{\frac{\sum |Y - F|^2}{n}} \tag{8.5}$$

Where Y = actual observations; F = forecast observations; and n = the number of observations.

MAD and RMSE Analysis

The above performance statistics for the wheel loader model (model number I) produced a MAD of 5.34 per cent and a RMSE of 8.44 per cent for the ARIMA (1,1,0) model. Considering that the plant breakdown percentage range was 12.86 per cent (12.86-0.00) over the 43-week period analysed, the forecasting accuracy of the ARIMA (1,1,0) model is substantiated. This evaluation was conducted for all the models and a summary of the results are presented in Table 8.4. The summary of the accuracies of the predictions when compared with actual BDPERC values are also given in Table 8.4. These results show that the models exhibit an average accuracy of 78 percent across board.

Also, details of the results from the spreadsheet computations are given in Tables 8.5, 8.6, 8.7 and 8.8 for the wheel loader, hydraulic excavator, backhoe-loader and the off-highway hauler models respectively. The tables also enhance a visual comparative analysis of the values obtained as predicted BDPERC against the actual values. All the computations for the MAD, RMSE and the range for each of the data sets were also given in the tables.

Table 8.4: Summary of the MAD, RMSE and Accuracy Analysis for the four Models

MODEL NUMBER	PLANT TYPE	MAD (%)	RMSE (%)	ACTUAL RANGE (%)	ACCURACY OF PREDICTIONS (%)
1	Wheel Loader	5.34	8.44	12.86	90.00
2	Backhoe Loader	7.05	8.93	40.91	75.00
3	Hydraulic Excavator	8.13	11.18	29.50	95.00
4	Off-Highway Hauler	27.06	29.79	69.81	52.00

Table 8.5: MAD and RMSE Analysis for the Wheel Loader BDPERC Model

	(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)
WEEK	FLTPERC	SBPERC	UTILPERC	BDPERC	Proj. %BD	(D) - (E)	(D-E)^2	ABS(D-E)
2	0.000	11.429	88.571	0.000	0.000	0.000	0.000	0.000
3	0.000	10.680	89.320	0.000	3.626	-3.626	13.146	3.626
4	1.920	0.000	98.667	1.429	3.684	-2.255	5.085	2.255
5	0.000	4.762	95.238	0.000	2.860	-2.860	8.181	2.860
6	0.000	2.857	97.143	0.000	4.140	-4.140	17.139	4.140
7	0.000	0.000	100.000	0.000	4.287	-4.287	18.377	4.287
8	0.000	0.000	100.000	0.000	4.507	-4.507	20.316	4.507
9	0.000	0.000	100.000	0.000	4.507	-4.507	20.316	4.507
10	0.000	0.000	100.000	0.000	4.507	-4.507	20.316	4.507
11	0.000	0.000	100.000	0.000	4.507	-4.507	20.316	4.507
12	0.000	0.000	100.000	0.000	4.507	-4.507	20.316	4.507
13	0.000	0.000	100.000	0.000	4.507	-4.507	20.316	4.507
14	0.000	0.000	100.000	0.000	4.507	-4.507	20.316	4.507
15	0.000	5.952	94.048	0.000	4.507	-4.507	20.316	4.507
16	0.000	0.000	100.000	0.000	4.048	-4.048	16.388	4.048
17	0.000	1.429	98.667	0.000	4.507	-4.507	20.316	4.507
18	0.000	0.000	101.942	0.000	4.399	-4.399	19.351	4.399
19	0.000	0.625	104.500	0.000	4.547	-4.547	20.674	4.547
20	0.000	2.381	97.714	0.000	4.563	-4.563	20.825	4.563
21	3.850	3.810	94.857	1.429	4.326	-2.897	8.393	2.897
22	0.000	20.000	80.000	0.000	1.624	-1.624	2.638	1.624
23	0.000	0.000	0.000	0.000	2.965	-2.965	8.789	2.965
24	0.000	21.905	78.095	0.000	2.470	-2.470	6.102	2.470
25	0.000	20.000	80.000	0.000	2.818	-2.818	7.940	2.818
26	68.630	0.000	97.333	0.000	2.965	-2.965	8.789	2.965
27	0.000	0.000	100.000	0.000	-29.054	29.054	844.157	29.054
28	5.770	90.000	10.000	0.000	4.507	-4.507	20.316	4.507
29	55.770	7.143	90.095	2.857	-5.252	8.109	65.753	8.109
30	0.000	0.000	100.000	0.000	-24.694	24.694	609.773	24.694
31	0.000	0.000	100.000	0.000	4.507	-4.507	20.316	4.507
32	68.630	2.857	90.476	6.667	4.507	2.159	4.663	2.159
33	0.000	6.667	93.333	0.000	-32.541	32.541	1058.929	32.541
34	0.000	0.000	100.000	0.000	3.993	-3.993	15.945	3.993
35	0.000	0.000	100.000	0.000	4.507	-4.507	20.316	4.507
36	0.000	0.000	100.000	0.000	4.507	-4.507	20.316	4.507
37	0.000	22.596	77.500	0.000	4.507	-4.507	20.316	4.507
38	0.000	11.538	88.462	0.000	2.766	-2.766	7.653	2.766
39	3.850	1.905	85.333	12.857	3.617	9.240	85.375	9.240
40	0.000	0.000	100.000	0.000	-3.922	3.922	15.380	3.922
41	5.770	22.857	76.190	0.952	4.507	-3.555	12.637	3.555
42	0.000	51.905	48.190	0.000	-0.547	0.547	0.299	0.547
43	0.000	0.000	100.000	0.000	0.506	-0.506	0.256	0.506
44	0.000	0.000	100.000	0.000	4.507	-4.507	20.316	4.507
45	5.770	0.952	95.238	3.810	4.507	-0.698	0.487	0.698
46	0.000	42.718	57.282	0.000	-0.281	0.281	0.079	0.281

RANGE	RMSE	MAD
12.857	8.443	5.336

Table 8.6: MAD and RMSE Analysis for the Backhoe-Loader BDPERC Model

WEEK	(A) FLTPERC	(B) SBPERC	(C) UTILPERC	(D) BDPERC	(E) Proj. %BD	(F) (D) - (E)	(G) (D-E)^2	(H) ABS (D-E)
2	4.030	18.636	64.545	16.818	0.000	16.818	282.851	16.818
3	2.900	10.455	48.727	40.909	1.280	39.629	1570.462	39.629
4	0.000	2.727	97.273	0.000	-8.609	8.609	74.113	8.609
5	4.030	5.455	93.636	0.909	6.756	-5.847	34.185	5.847
6	2.580	4.545	83.636	11.455	7.525	3.930	15.443	3.930
7	0.000	9.091	90.909	0.000	2.941	-2.941	8.649	2.941
8	0.000	10.909	89.091	0.000	6.783	-6.783	46.008	6.783
9	5.150	26.818	72.364	0.909	6.791	-5.882	34.593	5.882
10	0.000	19.091	80.909	0.000	7.927	-7.927	62.829	7.927
11	0.000	14.545	85.455	0.000	6.825	-6.825	46.587	6.825
12	2.420	6.364	89.091	4.545	6.806	-2.261	5.111	2.261
13	0.000	5.909	95.091	0.000	5.642	-5.642	31.833	5.642
14	0.000	18.182	82.727	0.000	6.774	-6.774	45.881	6.774
15	0.000	52.500	47.500	0.000	6.825	-6.825	46.586	6.825
16	0.000	47.201	51.592	0.000	6.967	-6.967	48.545	6.967
17	0.000	41.000	49.000	0.000	6.940	-6.940	48.162	6.940
18	0.000	75.556	35.556	0.000	6.877	-6.877	47.293	6.877
19	1.610	67.273	23.636	9.091	7.112	1.979	3.918	1.979
20	0.000	82.727	17.273	0.000	3.876	-3.876	15.024	3.876
21	0.000	74.545	25.455	0.000	7.096	-7.096	50.351	7.096
22	0.000	0.000	0.000	0.000	7.061	-7.061	49.859	7.061
23	0.000	82.979	17.021	0.000	6.329	-6.329	40.054	6.329
24	0.000	0.000	0.000	0.000	7.097	-7.097	50.366	7.097
25	0.000	72.727	27.273	0.000	6.329	-6.329	40.054	6.329
26	0.000	21.818	75.455	2.727	7.053	-4.326	18.715	4.326
27	2.580	45.455	54.545	0.000	5.757	-5.757	33.142	5.757
28	0.000	34.000	66.000	0.000	7.653	-7.653	58.565	7.653
29	0.000	14.545	78.182	7.273	6.889	0.384	0.147	0.384
30	2.420	30.909	69.091	0.000	3.926	-3.926	15.412	3.926
31	0.000	96.364	3.636	0.000	7.547	-7.547	56.952	7.547
32	0.000	70.000	30.000	0.000	7.154	-7.154	51.177	7.154
33	0.000	23.636	75.455	0.909	7.042	-6.133	37.610	6.133
34	2.010	19.091	71.818	0.000	6.485	-6.485	42.052	6.485
35	0.000	41.500	48.600	0.000	7.345	-7.345	53.948	7.345
36	0.000	85.556	36.667	0.000	6.880	-6.880	47.328	6.880
37	0.000	89.545	10.545	0.000	7.200	-7.200	51.843	7.200
38	0.000	0.000	0.000	0.000	7.125	-7.125	50.768	7.125
39	0.000	0.000	0.000	0.000	6.329	-6.329	40.054	6.329
40	0.000	91.818	8.182	0.000	6.329	-6.329	40.054	6.329
41	0.000	0.000	0.000	0.000	7.134	-7.134	50.901	7.134
42	0.000	0.000	0.000	0.000	6.329	-6.329	40.054	6.329
43	0.000	0.000	0.000	0.000	6.329	-6.329	40.054	6.329
44	0.000	0.000	0.000	0.000	6.329	-6.329	40.054	6.329
45	0.000	0.000	0.000	0.000	6.329	-6.329	40.054	6.329

RANGE		RMSE	MAD
40.909	Sum	3507.638	310.263
	Number	44.000	44.000
		79.719	7.051
		8.929	

Table 8.7: MAD and RMSE Analysis for the Hydraulic Excavator BDPERC

WEEK	(A) FLTPERC	(B) SBPERC	(C) UTILPERC	(D) BDPERC	(E) Proj. %BD	(F) (D) - (E)	(G) (D-E)^2	(H) ABS(D-E)
2	0.000	7.000	93.000	0.000	0.000	0.000	0.000	0.000
3	0.000	18.000	82.000	0.000	-7.456	7.456	55.599	7.456
4	0.000	8.000	92.000	0.000	-6.850	6.850	46.926	6.850
5	5.070	13.000	79.600	0.000	-7.401	7.401	54.781	7.401
6	2.010	15.000	80.000	7.500	-2.853	10.353	107.192	10.353
7	0.000	2.000	98.000	0.000	-9.308	9.308	86.645	9.308
8	2.580	7.500	88.600	4.000	-7.732	11.732	137.641	11.732
9	2.580	8.000	78.000	14.000	-7.457	21.457	460.411	21.457
10	2.740	3.000	73.000	24.000	-12.166	36.166	1308.003	36.166
11	0.000	0.000	0.000	0.000	-17.070	17.070	291.385	17.070
12	0.000	0.000	0.000	0.000	0.037	-0.037	0.001	0.037
13	2.010	0.000	99.000	1.000	0.037	0.963	0.928	0.963
14	0.000	5.000	95.000	0.000	-6.854	6.854	46.978	6.854
15	0.000	6.250	93.750	0.000	-7.567	7.567	57.255	7.567
16	2.010	1.250	95.750	3.125	-7.498	10.623	112.845	10.623
17	0.000	5.500	94.600	0.000	-7.803	7.803	60.891	7.803
18	2.420	4.000	66.600	29.500	-7.547	37.047	1372.483	37.047
19	0.000	0.000	0.000	0.000	-19.865	19.865	394.624	19.865
20	2.010	0.000	95.600	4.500	0.037	4.463	19.921	4.463
21	0.000	6.000	94.000	0.000	-8.523	8.523	72.634	8.523
22	0.000	28.500	71.600	0.000	-7.512	7.512	56.424	7.512
23	0.000	13.000	87.000	0.000	-6.279	6.279	39.432	6.279
24	2.580	24.000	62.600	13.500	-7.126	20.626	425.425	20.626
25	0.000	2.000	98.000	0.000	-11.055	11.055	122.217	11.055
26	0.000	14.000	86.000	0.000	-7.732	7.732	59.785	7.732
27	0.000	22.000	78.000	0.000	-7.071	7.071	49.995	7.071
28	0.000	48.000	52.000	0.000	-6.630	6.630	43.955	6.630
29	0.000	28.000	72.000	0.000	-5.197	5.197	27.008	5.197
30	0.000	91.000	9.000	0.000	-6.299	6.299	39.679	6.299
31	0.000	9.500	90.600	0.000	-2.827	2.827	7.993	2.827
32	0.000	28.000	72.000	0.000	-7.327	7.327	53.679	7.327
33	0.000	98.000	2.000	0.000	-6.299	6.299	39.679	6.299
34	0.000	71.000	29.000	0.000	-2.441	2.441	5.960	2.441
35	2.580	10.000	82.500	7.500	-3.929	11.429	130.630	11.429
36	0.000	64.000	36.000	0.000	-8.972	8.972	80.499	8.972
37	0.000	0.000	0.000	0.000	-4.315	4.315	18.620	4.315
38	0.000	30.500	69.600	0.000	0.037	-0.037	0.001	0.037
39	0.000	20.000	80.000	0.000	-6.169	6.169	38.060	6.169
40	0.000	65.000	35.000	0.000	-6.740	6.740	45.428	6.740
41	0.000	0.000	0.000	0.000	-4.260	4.260	18.148	4.260
42	0.000	8.000	92.000	0.000	0.037	-0.037	0.001	0.037
43	0.000	0.000	0.000	0.000	-7.401	7.401	54.781	7.401
44	0.000	4.000	96.000	0.000	0.037	-0.037	0.001	0.037
45	0.000	50.800	49.000	0.000	-7.622	7.622	58.092	7.622
46	0.000	0.000	0.000	0.000	-5.027	5.027	25.269	5.027
47	0.000	0.000	0.000	0.000	0.037	-0.037	0.001	0.037
48	0.000	0.000	0.000	0.000	0.037	-0.037	0.001	0.037

Table 8.7 Continued

WEEK	(A) FLTPERC	(B) SBPERC	(C) UTILPERC	(D) BDPERC	(E) Proj. %BD	(F) (D) - (E)	(G) (D-E)^2	(H) ABS(D-E)
49	0.000	0.000	0.000	0.000	0.037	-0.037	0.001	0.037
50	0.000	0.000	0.000	0.000	0.037	-0.037	0.001	0.037
51	0.000	0.000	0.000	0.000	0.037	-0.037	0.001	0.037

RANGE		RMSE	MAD
29.500	Sum	6127.915	391.065
	Number	50.000	50.000
		122.558	**7.821**
		11.071	

Table 8.8: MAD and RMSE Analysis for the Off-Highway Hauler BDPERC Model

WEEK	(A) FLTPERC	(B) SBPERC	(C) UTILPERC	(D) BDPERC	(E) Proj. %BD	(F) (D) - (E)	(G) (D-E)^2	(H) ABS(D-E)
2	0.000	21.818	78.182	0.000	0.000	0.000	0.000	0.000
3	0.000	18.636	63.273	0.000	-24.962	24.962	623.094	24.962
4	2.420	24.545	73.636	1.818	-18.351	20.170	406.810	20.170
5	0.000	53.182	46.909	0.000	-16.457	16.457	270.849	16.457
6	2.420	7.273	91.818	0.909	-19.419	20.328	413.234	20.328
7	0.000	14.091	86.000	0.000	-19.550	19.550	382.208	19.550
8	1.610	22.273	76.000	1.818	-26.372	28.191	794.710	28.191
9	2.420	19.737	57.544	22.807	-19.568	42.375	1795.676	42.375
10	0.000	6.356	93.729	0.000	-16.880	16.880	284.946	16.880
11	1.530	15.086	75.862	9.052	-27.746	36.798	1354.061	36.798
12	0.000	5.833	94.167	0.000	-20.913	20.913	437.369	20.913
13	0.000	6.250	97.167	0.000	-27.805	27.805	773.128	27.805
14	0.000	6.250	93.833	0.000	-29.086	29.086	846.020	29.086
15	0.000	13.889	81.778	0.000	-27.764	27.764	770.847	27.764
16	0.000	8.163	91.837	0.000	-24.653	24.653	607.785	24.653
17	2.420	5.417	94.167	0.417	-27.391	27.807	773.252	27.807
18	0.000	7.273	81.818	0.000	-19.891	19.891	395.662	19.891
19	0.000	4.592	95.510	0.000	-23.222	23.222	539.244	23.222
20	1.610	17.083	81.333	1.667	-28.066	29.733	884.061	29.733
21	1.610	9.583	81.333	7.500	-20.492	27.992	783.543	27.992
22	1.610	3.774	26.415	69.811	-21.035	90.846	8253.035	90.846
23	0.000	23.039	77.059	0.000	-21.309	21.309	454.080	21.309
24	0.000	27.500	73.000	0.000	-24.784	24.784	614.225	24.784
25	0.000	5.000	95.000	0.000	-24.150	24.150	583.200	24.150
26	0.000	5.000	95.000	0.000	-27.953	27.953	781.394	27.953
27	0.000	25.833	74.167	0.000	-27.953	27.953	781.394	27.953
28	0.000	27.917	72.167	0.000	-24.248	24.248	587.949	24.248
29	0.000	6.250	93.833	0.000	-23.910	23.910	571.695	23.910
30	2.420	5.000	82.167	7.500	-27.764	35.264	1243.559	35.264
31	0.000	5.833	89.167	0.000	-17.692	17.692	313.007	17.692
32	0.000	17.917	83.333	0.000	-25.822	25.822	666.762	25.822
33	0.000	10.833	76.667	0.000	-26.152	26.152	683.912	26.152

Table 8.8 Continued

WEEK	(A) FLTPERC	(B) SBPERC	(C) UTILPERC	(D) BDPERC	(E) Proj. %BD	(F) (D) - (E)	(G) (D-E)^2	(H) ABS(D-E)
34	0.000	6.667	59.667	0.000	-21.957	21.957	482.118	21.957
35	0.000	5.556	96.296	0.000	-14.302	14.302	204.540	14.302
36	0.000	49.490	106.735	0.000	-28.589	28.589	817.343	28.589
37	0.000	13.333	86.667	0.000	-42.343	42.343	1792.964	42.343
38	0.000	12.917	87.167	0.000	-26.471	26.471	700.720	26.471
39	0.000	12.083	88.000	0.000	-26.578	26.578	706.405	26.578
40	0.000	28.750	71.333	0.000	-26.727	26.727	714.307	26.727
41	0.000	52.917	47.167	0.000	-23.762	23.762	564.628	23.762
42	2.900	6.250	91.333	2.500	-19.463	21.963	482.383	21.963
43	1.530	4.545	88.182	7.273	-18.147	25.420	646.170	25.420
44	1.530	4.091	63.273	32.727	-22.828	55.555	3086.381	55.555
45	2.420	23.636	70.909	5.455	-22.378	27.833	774.659	27.833
46	0.000	11.364	88.727	0.000	-16.538	16.538	273.514	16.538
47	0.000	23.636	76.364	0.000	-26.858	26.858	721.327	26.858
48	1.530	7.727	68.727	23.636	-24.638	48.275	2330.457	48.275
49	0.000	29.545	70.545	0.000	-21.934	21.934	481.088	21.934
50	0.000	53.500	46.600	0.000	-23.623	23.623	558.066	23.623
51	0.000	0.000	0.000	0.000	-19.366	19.366	375.045	19.366

RANGE		RMSE	MAD
69.811	Sum	44382.827	1352.756
	Number	50.000	50.000
		887.657	27.055
		29.794	

These results show that the hydraulic excavator and the off-highway hauler prediction models indicated the weakest performance statistics. MAD for the items were 7.82 and 27.05 percent respectively, while the RMSE were 11.07 and 29.79 respectively. These were higher than those of the wheel loader and backhoe-loader BDPERC prediction models, which had a performance statistics 5.34 and 7.05 per cent MAD and 8.44 and 8.93 per cent RMSE respectively. However, an observation of the range of actual BDPERC values indicated that the range for the hydraulic excavators and the off-highway loaders (69.81 and 29.50) were averagely much higher than those of the other two plant types (12.86 and 40.91). This can be inferred to indicate that the predictive capabilities of the models, although satisfactory, could be weaker when the range of actual observations of BDPERC increases. Such changes could be as a result of drastic changes in plant operating and/or maintenance conditions within the period of observation.

ANOVA

In the ANOVA model, the observed data set was represented as 'A' and the predicted data set was represented as 'B' for the wheel loader prediction model and the results were used as a generalised case. This generalisation was based on the ANCOVA results that had provided confirmatory evidence that the four independent variables considered were significant contributors to all the BDPERC prediction models.

In order to ascertain that the variations between the predicted values were not purely due to chance, therefore, a formal statement of the null and alternative hypotheses was made as: H0: $\mu A = \mu B$; H1: $\mu A \neq \mu B$; where μA, μB are sample means of the data sets A (predicted breakdown) and B (actual breakdown) respectively.

Generally, average values may differ for the observed and predicted values. This may be due to the influence of the faults occurrence, previous breakdown, utilisation and standby times on the prediction and also as a result of chance. If the null hypothesis is true, the variation is due to chance only. If the null hypothesis is false, the variation is due to both the prediction and chance (Ruddock, 1995).

The measure of the actual variation, $S^2_{\bar{x}_i t}$, is given as:

$$S^2_{\bar{x}_i t} = \frac{\sum \left(\bar{x}_i - \bar{\bar{x}}\right)^2}{k-1} \qquad (8.6)$$

Where: $\bar{x}$ is the overall mean of the total data; $\bar{x}_i$ is the individual sample means; and k is the number of sample means.

If the null hypothesis is true, the two samples are drawn from the normal populations with the same mean, μ, and variance, σ2. The F-distribution is described with [k-1, k (n-1)] degrees of freedom (where k=2 and n=45).

For the datasets, the number of the degrees of freedom are (1, 88) and the F distribution is 17.575. From the F-distribution table, with a level of significance of 0.05, the critical value for F=0.05 is 3.98. Hence, since F distribution >> F0.05, the null hypothesis was therefore rejected at the 0.05 level of significance. It was therefore validated that the independent variables are strong predictors of percentage of BDPERC.

Non-Parametric Wilcoxon Test

It was also considered that the use of parametric techniques to validate the work may be seriously flawed since datasets A and B are not independent, Hence, a non-parametric 'Wilcoxon test' was carried out on all the model building datasets. Like the t-test for correlated samples, the Wilcoxon signed-ranks test applies to two-sample designs involving repeated measures, matched pairs, or "before" and "after" measures (Stuttard, 1994). This test revealed that the predictions are not significantly different to the actual percentage breakdown. Thus the robustness of the models derived are further validated.

THE FORMULATION OF THE MBMS

The INTELLIPLANT MBMS is based on the assemblage of the four validated ARIMA models developed. The models enable the prediction of plant breakdown as a percentage of anticipated hours of work by individual plant items. The formulation of the MBMS, therefore, follows a four-phase methodology. First, the structure of the MBMS was defined in order to enable a definition of the information/process logic. Second, the model base and directory were defined with a view to facilitate the development of key identifiers of each model within the MBMS. Third, the SQL syntax and computational logic used for the model management were defined and fourth the model execution procedure was established.

Structure of the INTELLIPLANT MBMS

The structure of the INTELLIPLANT MBMS was created to ensure unique capabilities such as a low overhead and efficiency. This was intended to guarantee optimal performance on computers with modest hardware configurations. The structure of the MBMS is outlined in Figure 8.18.

The entire MBMS and RDBMS were developed within the MS Access environment. This concept facilitated the optimal utilisation of the software for SQL development for the model base query and execution and VBA for the user interface. A more detailed description of each of the sub-components of the MBMS now follows.

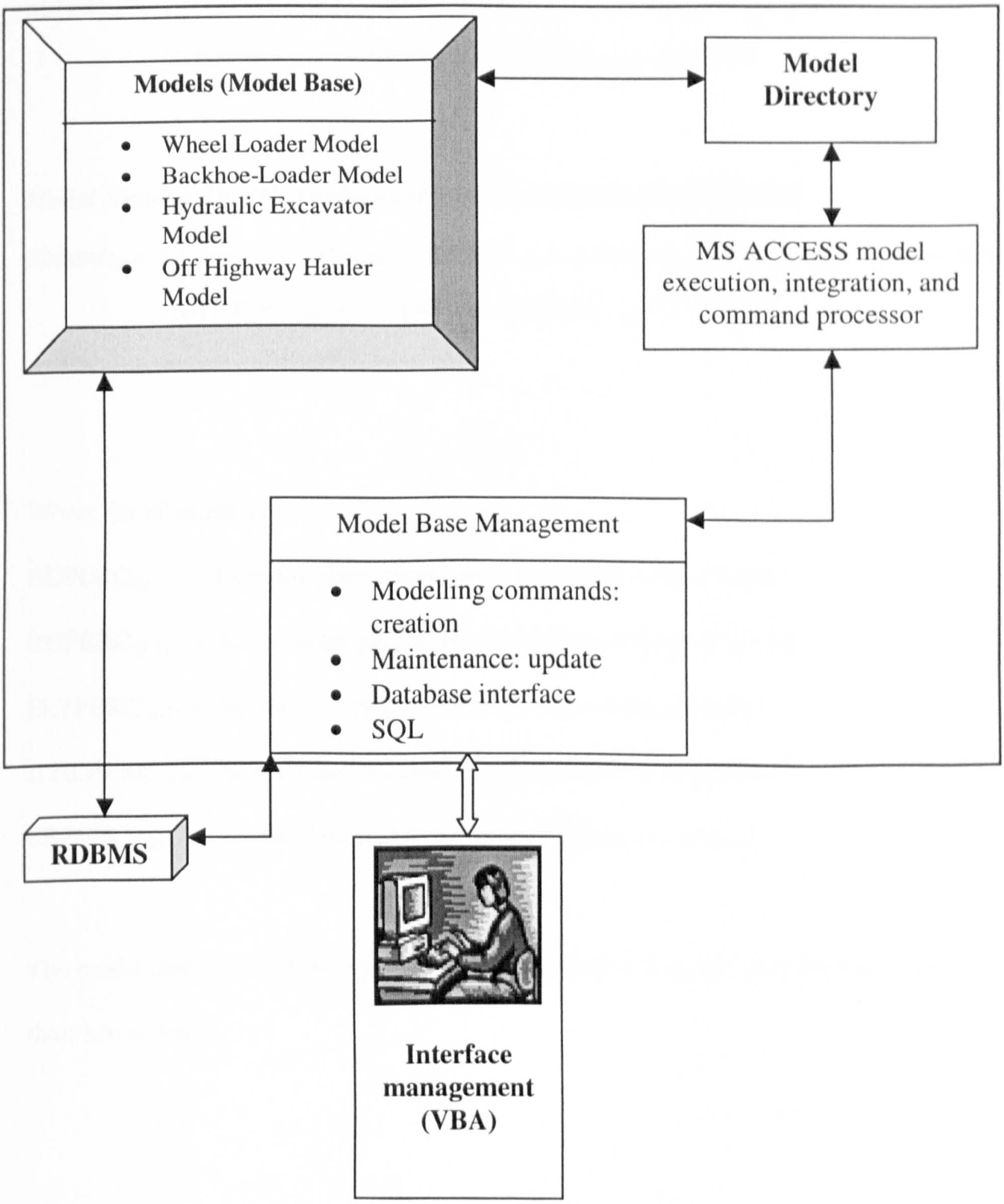
Model Base and Model Directory

The model base of the MBMS contains the four ARIMA models developed as part of this research. Details of each of the models are:

Model Number I: Wheel Loader Prediction Model (WLPM)

$$BDPERC_{(t)} = 0.01771729 + (-0.47774312) \times BDPERC_{(t-1)} + (-0.4882316) \times (FLTPERC)_{(t-1)} + (-0.01636534) \times (UTILPERC)_{(t-1)} + (-0.05676213) \times SBPERC_{(t-1)} + 2.452596$$

Figure 8.18: Final Structure of the INTELLIPLANT MBMS



Model Number II: Backhoe-Loader Prediction Model (BLPM)

$$BDPERC_{(t)} = 0.0094648 + (-0.39189477) \times BDPERC_{(t-1)} + (0.277260181) \times (FLTPERC)_{(t-1)} + (0.0041553) \times (UTILPERC)_{(t-1)} + (0.0084045) \times (SBPERC)_{(t-1)} + 6.319328$$

Model Number III: Hydraulic Excavator Prediction Model (HEPM)

$$BDPERC_{(t)} = -\ 0.65681235 + (-0.55324591) \times BDPERC_{(t-1)} + (0.72769287) \times (FLTPERC)_{(t-1)} + (-0.07878984) \times (UTILPERC)_{(t-1)} + (-0.02367837) \times (SBPERC)_{(t-1)} + 0.6935187$$

Model Number IV: Off-Highway Hauler Prediction Model (OHPM)

$$BDPERC_{(t)} = -0.5316621 + (-0.3744266) \times BDPERC_{(t-1)} + (3.2970114) \times (FLTPERC)_{(t-1)} + (-0.3966897) \times (UTILPERC)_{(t-1)} + (-0.2188132) \times (SBPERC)_{(t-1)} + 1.1357832$$

Where (in all models):

$BDPERC_{(t)}$ = Forecast plant breakdown percentage time at week t

$BDPERC_{(t-1)}$ = Actual plant percentage breakdown time at week t-1

$FLTPERC_{(t-1)}$ = Actual fault type percentage occurrence at week t-1

$UTILPERC_{(t-1)}$ = Actual plant percentage utilisation time at week t-1

$SBPERC_{(t-1)}$ = Actual plant percentage standby time at week t-1

The model directory is a listing of all the above models (model numbers 1 to 4) and their acronyms.

Model Base Management and Modelling Language

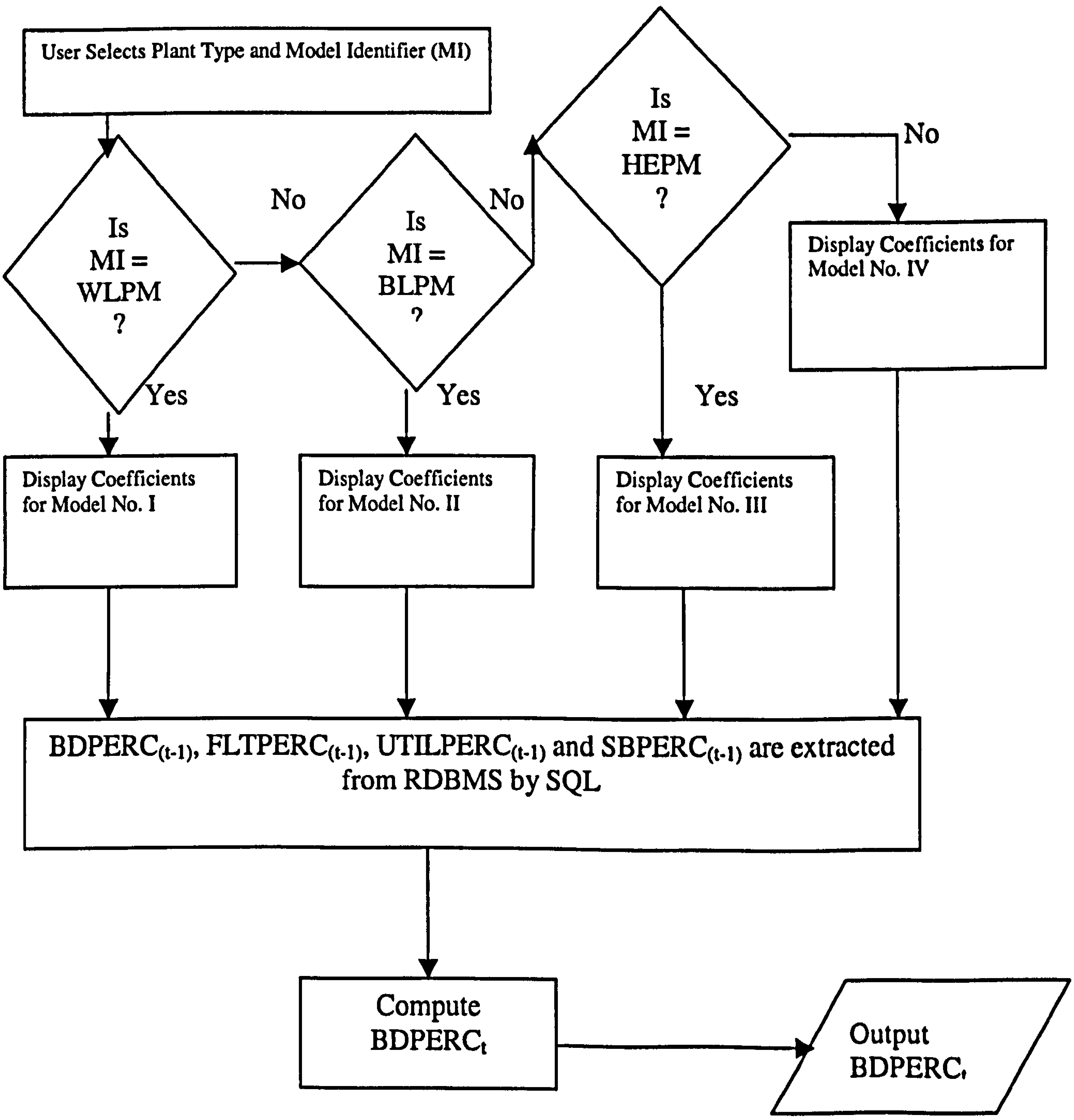
On accessing the MBMS, the user is presented with the option of the choice of models to be used within the model directory, which lists the models already stored in the model base (in real time). The models were given identifiers such as WLPM, BLPM, HEPM and OHPM for wheel loaders, backhoe loaders, hydraulic excavators and off-highway haulers respectively. These identifiers are also the primary keys within the relational database structure of the model base.

The model base management routine of the MBMS provides the user with VBA data access page. This page facilitates interactivity between the RDBMS and the MBMS through the model directory. This interactivity is based on incorporated SQL commands that are operating on a number of: IF.... AND...THEN.... SELECT rules. Hence, the user needs to specify the plant type and model. The required model is then selected automatically by INTELLIPLANT based on a definition of the equipment type made by the user when prompted by the system.

Model Execution

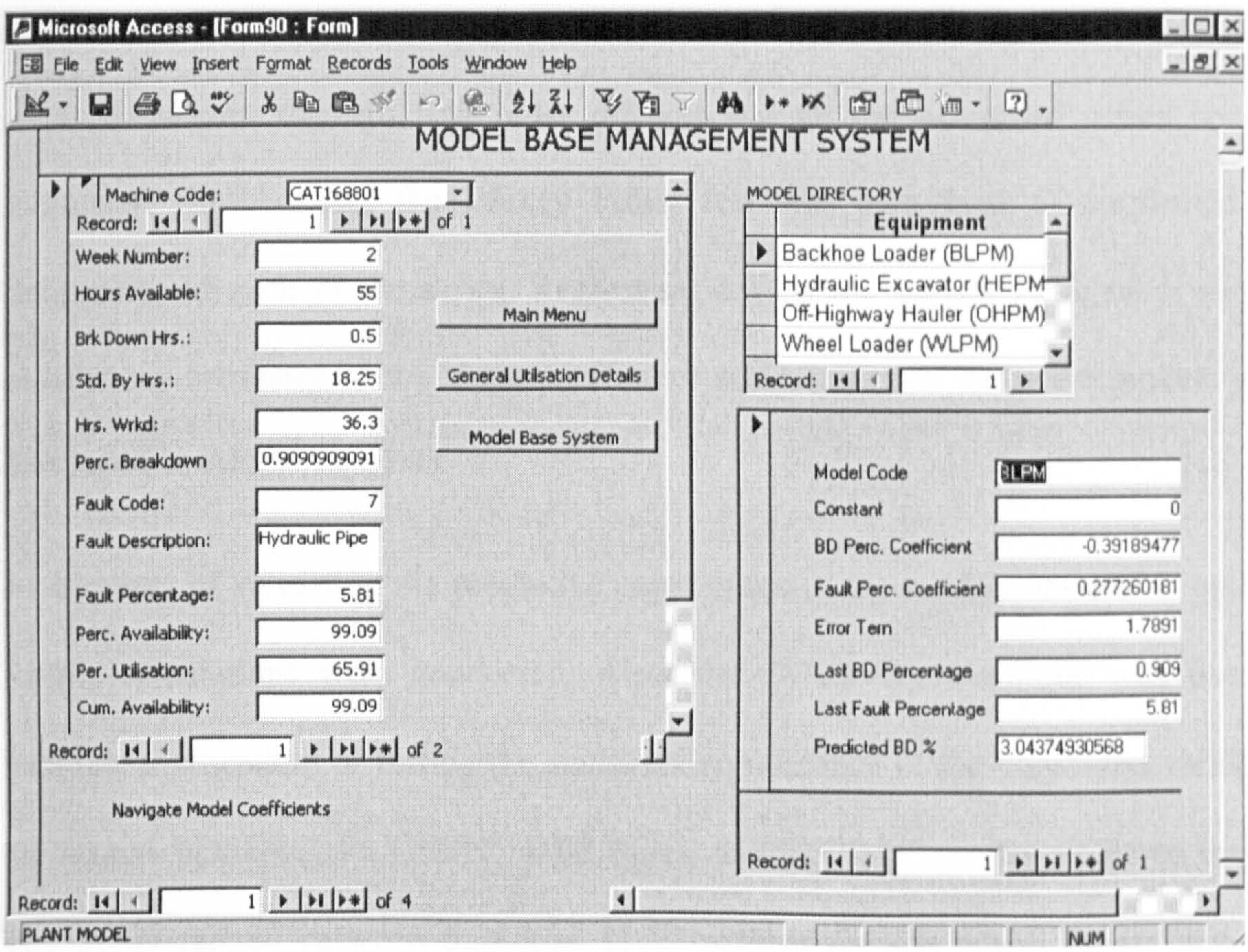
The final stage of the computational procedure for plant breakdown prediction is the model execution. At this stage, INTELLIPLANT utilises the selected model to compute plant breakdown predictions. The model called up from the model base selects the constant and error terms in addition to the coefficients of the independent variables (BDPERC, FLTPERC, UTILPERC and SBPERC), while the actual values of the $BDPERC_{(t-1)}$, $FLTPERC_{(t-1)}$, $UTILPERC_{(t-1)}$ and $SBPERC_{(t-1)}$ are selected automatically by INTELLIPLANT from the RDBMS. The model is the executed at the instance of the user and the forecast value of BDPERC is then displayed. Figure 8.19 is flowchart, which explains the model base management, and model execution system logic, while the GUI of the MBMS is illustrated in Figure 8.20.

Figure 8.19: Flowchart of the MBMS Process Logic



The display (Figure 8.19) explains the layout of the model directory, plant history input and breakdown prediction output sections of the MBMS. Also from this screen, users can navigate back to the main menu in order to access other parts of INTELILIPLANT.

Figure 8.20: GUI of the Model Base Management System



SUMMARY

A model building procedure based on the successful outcome of an exploratory analysis has been used in developing the MBMS of INTELLIPLANT. The development of the BDPERC models for the MBMS involved a three-stage simulation namely; a review of the historical data for the selected plant item; a time series analytical procedure based on the methodology established under the exploratory study; and model development/ validation process.

The time series modelling philosophy established for this development was founded upon the development of an ARIMA process. The lagged BDPERC, FLTPERC, UTILPERC and SBPERC were selected as the independent variables of the dependent variable (BDPERC). Plots of the sequence charts for BDPERC against time in weeks for historical data of the historical data revealed a non-stationary and non-seasonal series. However, through first order differencing all the examined series became stationary. Furthermore, the Dickey Fuller test was also used to confirmed the stationarity of each of the series. Regressing Δy_t on the lagged value of y_t yielded satisfactory estimates of the slope coefficient and t-statistics. Thus the models were developed as ARIMA (1,1,0).

As a means of validating the predictive capabilities of the models, the MAD and the RMSE calculations were conducted. Also, the (ANOVA) technique was used to facilitate a procedure of testing the statistical significance of the combined variables: the lagged BDPERC, FLTPERC, UTILPERC and SBPERC on the predicted results. The MAD ranged between 5.34 and 11.07 percent for the wheel loader and off-highway hauler prediction models respectively. The RMSE values also showed similar trends with the off-highway hauler prediction model yielding the highest value of 29.79 per cent. However, it was also observed that the range of actual BDPERC values was highest for the off-highway loaders. A situation, which signified that the predictive capabilities of the models could become weaker as the range of observed BDPERC increases.

The MBMS of INTELLIPLANT was developed as a system containing a library of the validated time series models, which can enhance the prediction the plant breakdown percentage time. The development of the MBMS followed a four-phase methodology. These were: the definition of the information/process logic structure of the MBMS; the creation of the model base and directory; the definition of the SQL syntax and computational logic used for the model management; and the establishment of the model execution procedure.

In terms of the operating principle of the MBMS, when the user selects a model from the model directory, INTELLIPLANT selects the constant and error terms. These are in addition to the selection of the coefficients of the independent variables (BDPERC, FLTPERC, UTILPERC and SBPERC) from the model base. The model is then executed at the instance of the user and the forecast value of BDPERC is then displayed. The GUI of the MBMS was designed to contain a layout of the model directory, plant history input and the breakdown percentage prediction output sections. It also ensures that users can navigate back to the main menu to facilitate access to other parts of INTELILIPLANT.

CHAPTER NINE: INTELLIPLANT- System Integration, Web Hosting and Performance Evaluation

INTRODUCTION

The development of INTELLIPLANT has been facilitated through the adoption of the Microsoft Access 2000 database software as a mono-software solution. The RDBMS facilitates data capture and reporting, while the MBMS facilitates the intelligent prediction of off-highway plant breakdown percentage as a function of hours of work anticipated for a plant item. The integration of these components was achieved by the use SQL commands and macros within the Microsoft Access environment.

This chapter focuses on the system integration technique, the web hosting methodology and the performance evaluation of the system. INTELLIPLANT was made web-enabled through the design and application of Data Access Pages. A procedure, which makes it possible for users to access individual, forms of a relational database through hyperlinked web pages.

The chapter also presented the performance evaluation conducted on INTELLIPLANT. Typical practitioner inputs/feedback were utilised for the evaluation. The collaborating organisations invited to participate in the performance evaluation exercise provided this inputs/feedback. The basis of evaluation included content, speed of connection/processing queries, data entry, reporting and general decision support. Details of the evaluation are hereby presented.

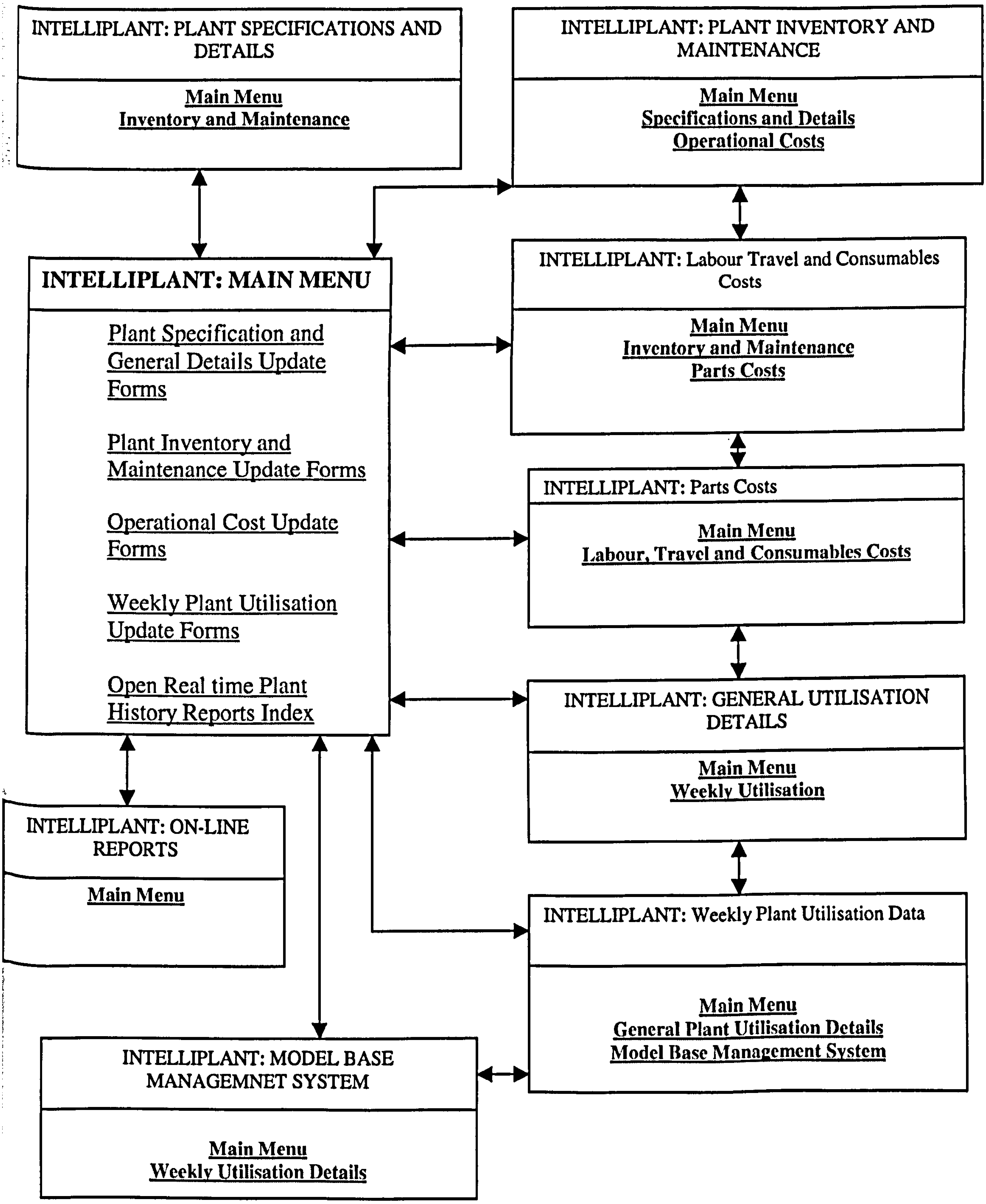
SYSTEM ARCHITECTURE

The system architecture of the web-enabled INTELLIPLANT was based on the interface previously developed for the RDBMS and the MBMS. Below is a brief description of the overview of the final system and the method in which the components were integrated.

Overview

The web enabled INTELIPLANT was designed using Data Access Pages. These pages enable access to the various forms contained in the database. The Data Access Pages also facilitate the access to the MBMS and history file reporting components of INTELLIPLANT. These web-enabled enhancements complete the process of permitting on-line data entry, report generation and plant breakdown time prediction by INTELLIPLANT. A flowchart of the web pages and their inter-page access through hyperlinks is given in Figure 9.1. In Figure 9.1, the title of the web-pages are shown in 'bold' at the top of each Data Access Page, while the hyperlinks contained on each page for navigation through INTELLIPLANT are shown in the underlined texts.

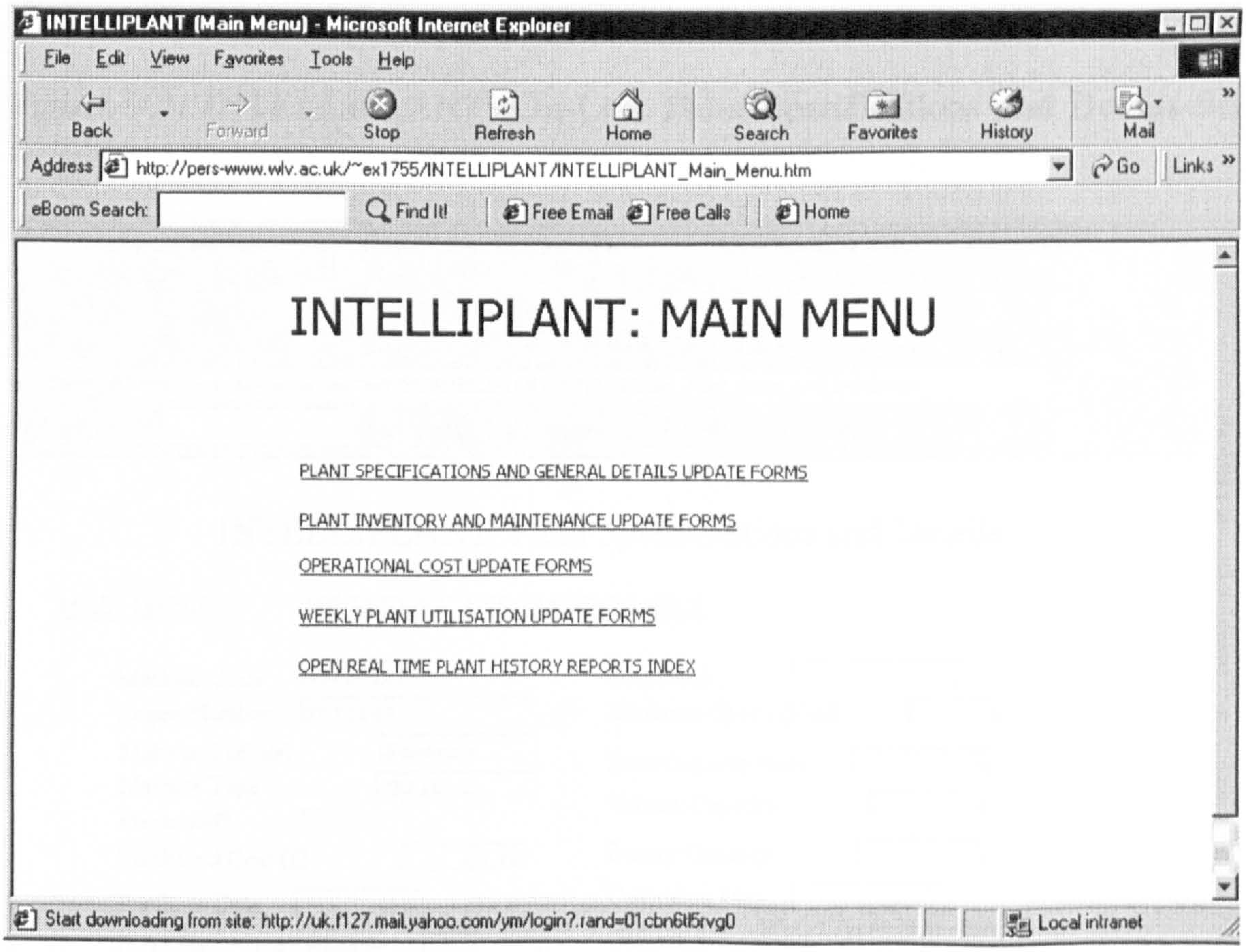
Figure 9.1: Web-Enabled Data Access Pages of INTELLIPLANT



ON-LINE GUI

Based on the navigation structure illustrated in Figure 9.1, the on-line system was developed and the web pages were designed to enable interaction with the INTELLIPLANT RDBMS/MBMS resident on the server. All through the developmental phase, prospective users were contacted for their perception of the GUI. Figures 9.2 to 9.10 are typical displays from 'finalised' versions of the various web pages of INTELLIPLANT.

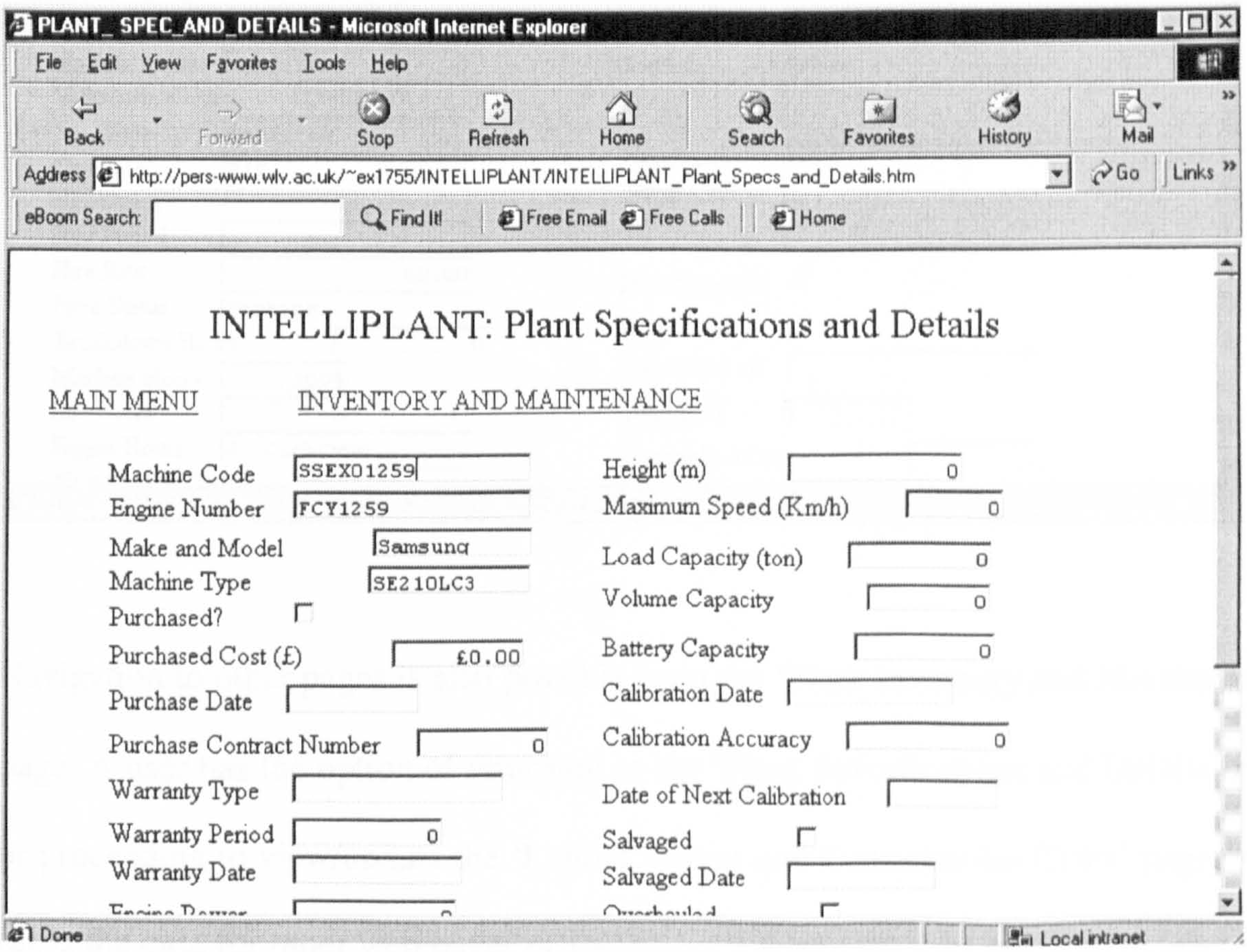
Figure 9.2: INTELLIPLANT: On-Line Main Menu Screen Display



The 'Main Menu' page is the first user interface that is opened on executing INTELLIPLANT. From here, users can navigate through the contents of INTELLIPLANT as necessary. Each of the other web pages are also accessible from this 'Main Menu' page and vice versa is explained as follows starting with the first link.

On clicking the PLANT SPECIFICATIONS AND GENERAL DETAILS UPDATE FORMS hyperlink of the 'Main Menu' page, users are navigated to the 'Plant Specifications and Details' page. This page allows an on-line visualisation of all the general details about plant items. It also allows record updates as may be appropriate. Links to the 'Main Menu' page and the 'Inventory and Maintenance' pages are also provided. Figure 9.3 is a sample display of the 'Plant Specifications and Details' page.

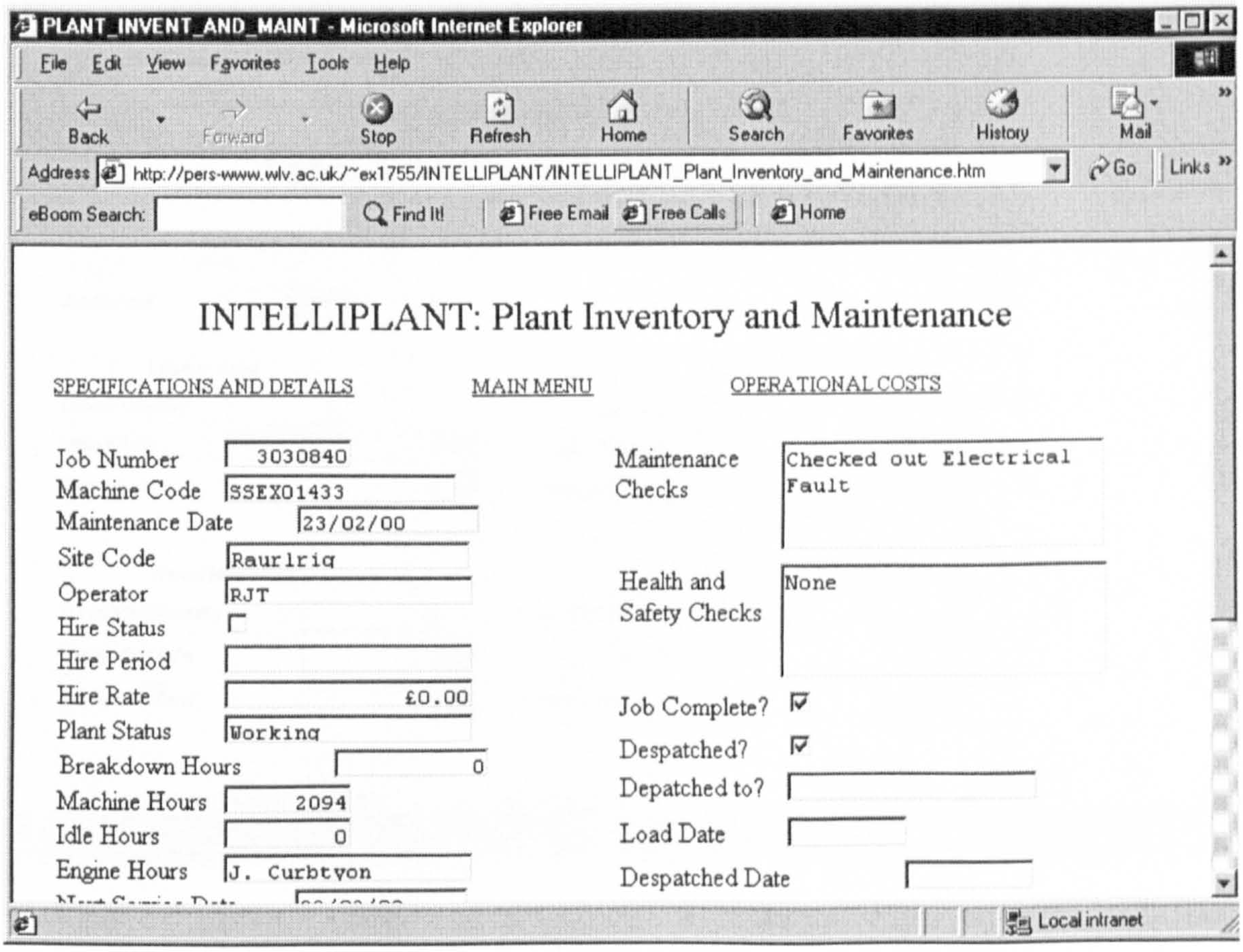
Figure 9.3: INTELLIPLANT: On-Line Plant Specifications and Details Screen Display



Two options exist for viewing the 'Plant Inventory and Maintenance' page. The first is by returning to the 'Main Menu' page and clicking on the PLANT INVENTORY

AND MAINTENANCE UPDATE FORMS hyperlink, while the second is by clicking on the INVENTORY AND MAINTENANCE hyperlink on the 'Plant Specifications and Details' page. A typical display of the GUI of the 'Plant Inventory and Maintenance' page is given in Figure 9.4.

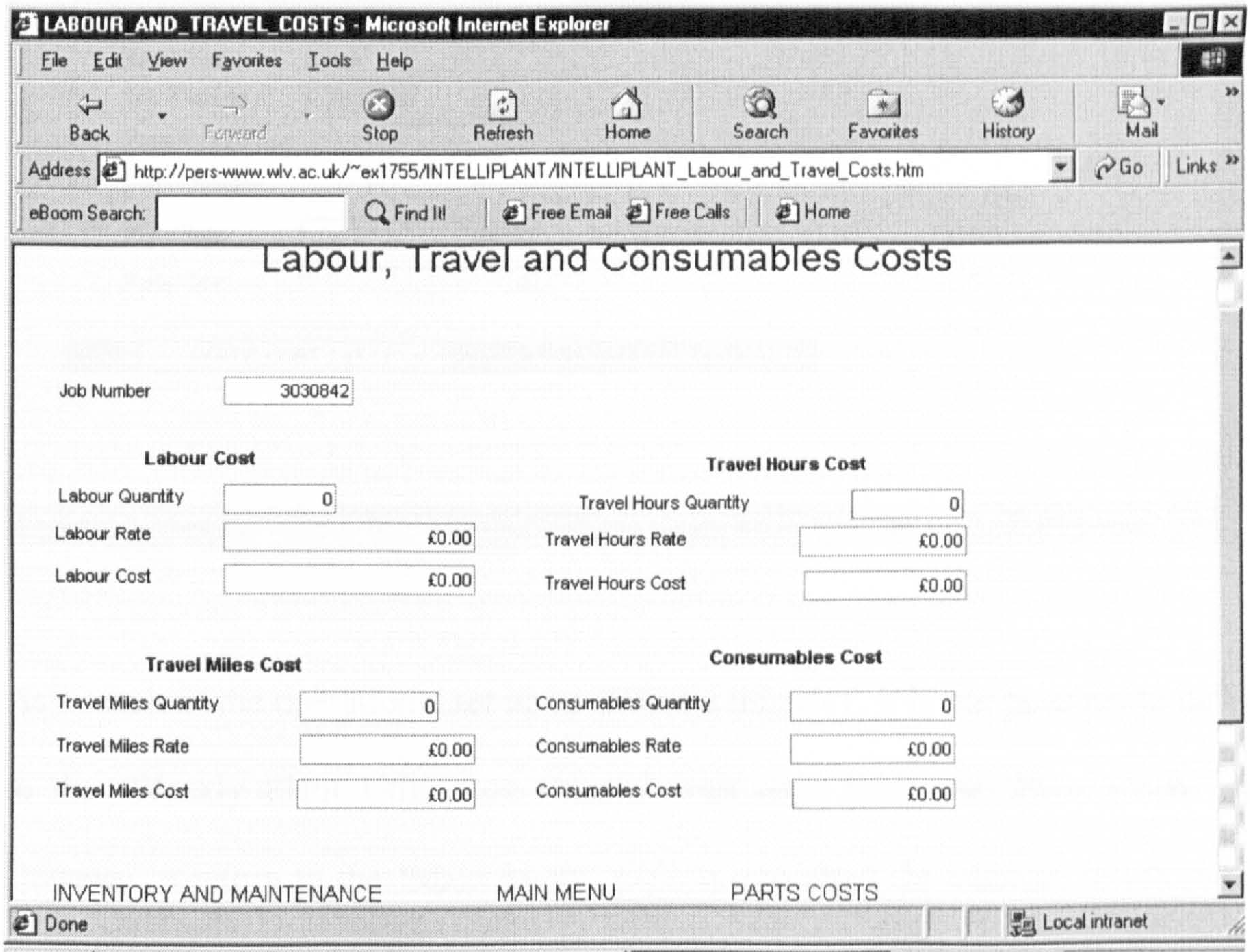
Figure 9.4: INTELLIPLANT: On-Line Plant Inventory and Maintenance Screen Display



Navigation to other pages is also possible from the 'Plant Inventory and Maintenance' page. A user has the option of returning to the 'Plant Specifications and Details' page or proceeding to view/update the 'Labour Travel and Consumables Costs' page. Also (as is the case for other web pages of INTELLIPLANT) the user can also return to the 'Main Menu' Page. The hyperlinks embedded into the 'Plant Inventory and Maintenance' as shown in Figure 9.4 facilitate this. In order to navigate to the

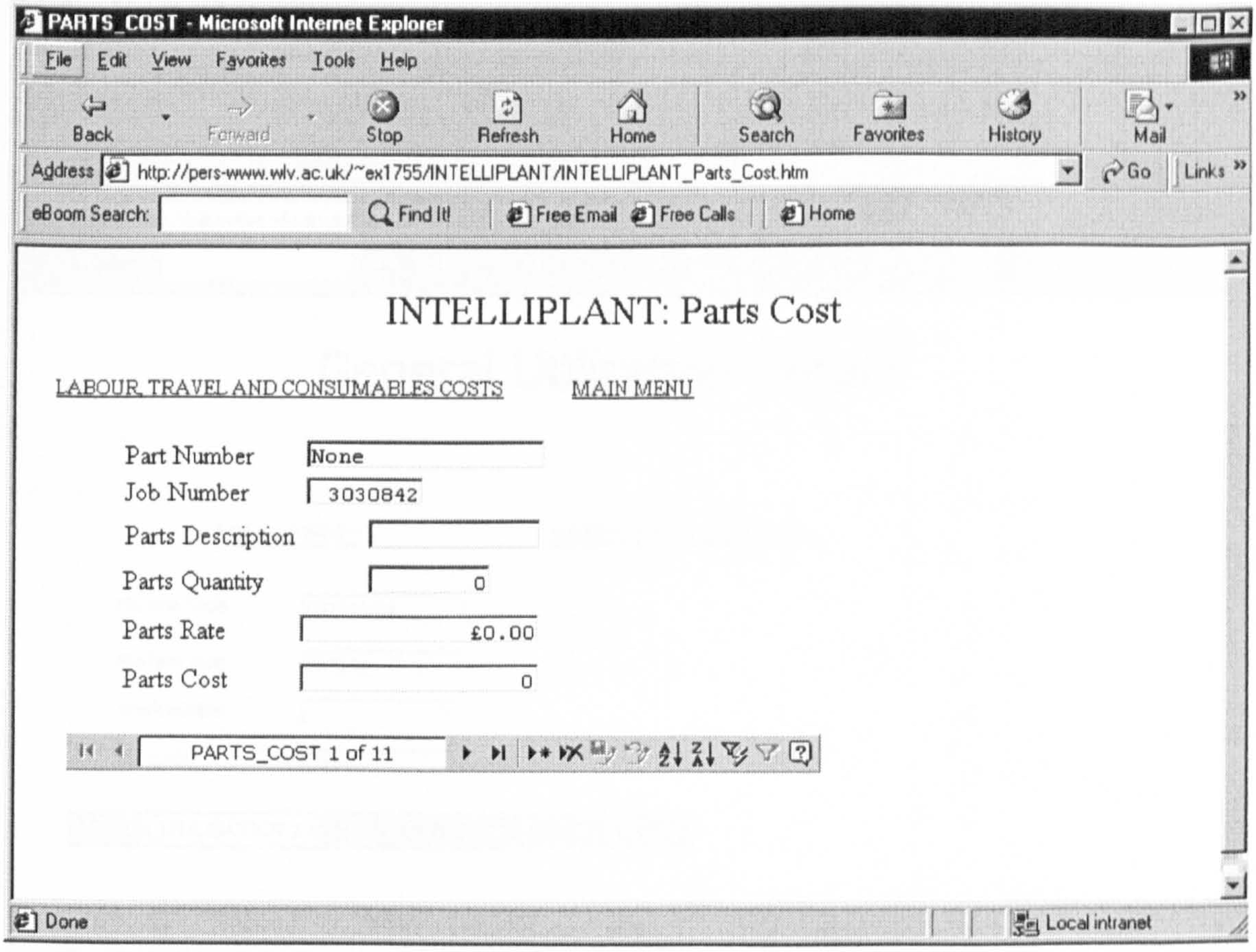
'Labour, Travel and Consumables Costs' page, the user is required to click on the OPERATIONAL COSTS Hyperlink which initiates access to the first set of operational cost forms (Figure 9.5).

Figure 9.5: INTELLIPLANT: On-Line Labour, Travel and Maintenance Costs Screen Display



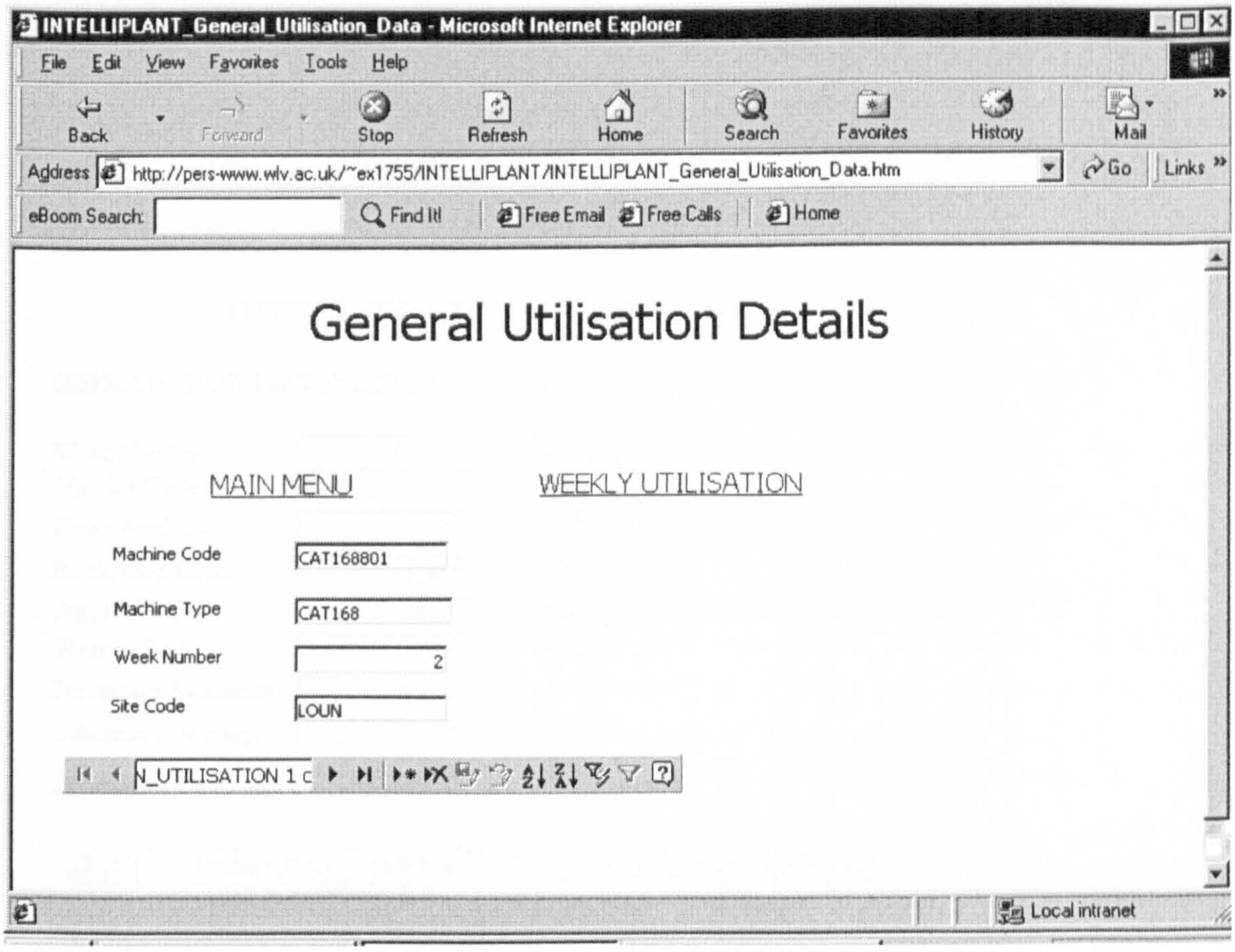
Also, as shown in Figure 9.6, the user can navigate to the 'Parts Costs' page after filling in the details relating to the Labour, Travel and Consumables Costs. The details of parts costs have been separated, as the records are independent from the Labour, Travel and Consumables Costs.

Figure 9.6: INTELLIPLANT: On-Line Parts Cost Screen Display



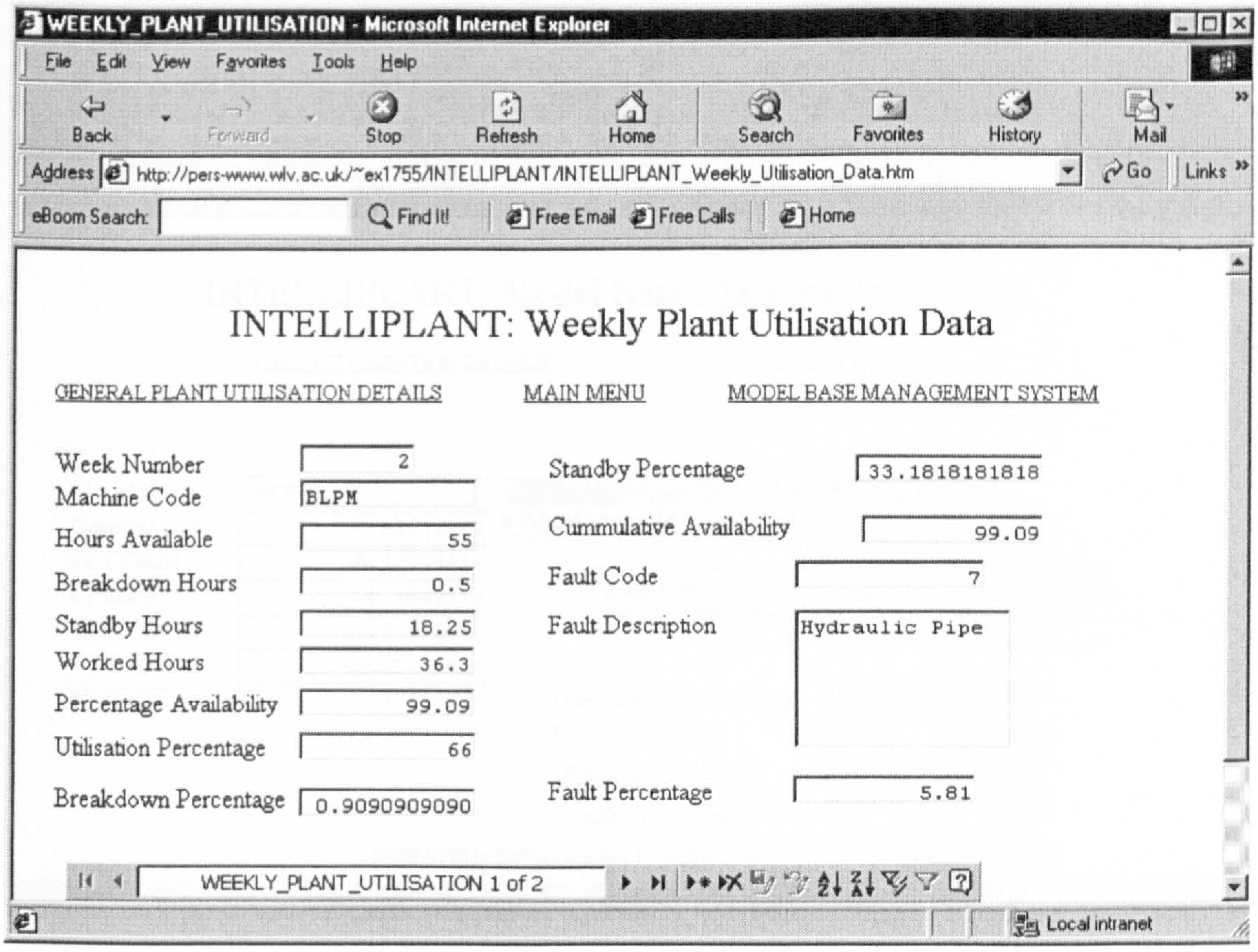
As a result of the operational set up of INTELLIPLANT, it is not possible to navigate to the 'Weekly Plant Utilisation Details' web page from the 'Parts Costs' page. However, a return to the 'Main Menu' page is permitted (in addition to returning to the 'Labour, Travel and Consumables Costs' page). From the 'Maim Menu' page the user may then access the first part of the 'Weekly Plant Utilisation Details' web pages (i.e. 'General Utilisation Details') by clicking on the <u>WEEKLY PLANT UTILISATION UPDATE FORMS</u> hyperlink. Figure 9.7 illustrates the layout of the 'General Utilisation Details' page, which allows the viewing, and updating of the general details that relate to the utilisation of plant items on a weekly basis.

Figure 9.7: INTELLIPLANT: On-Line General Utilisation Details Screen Display



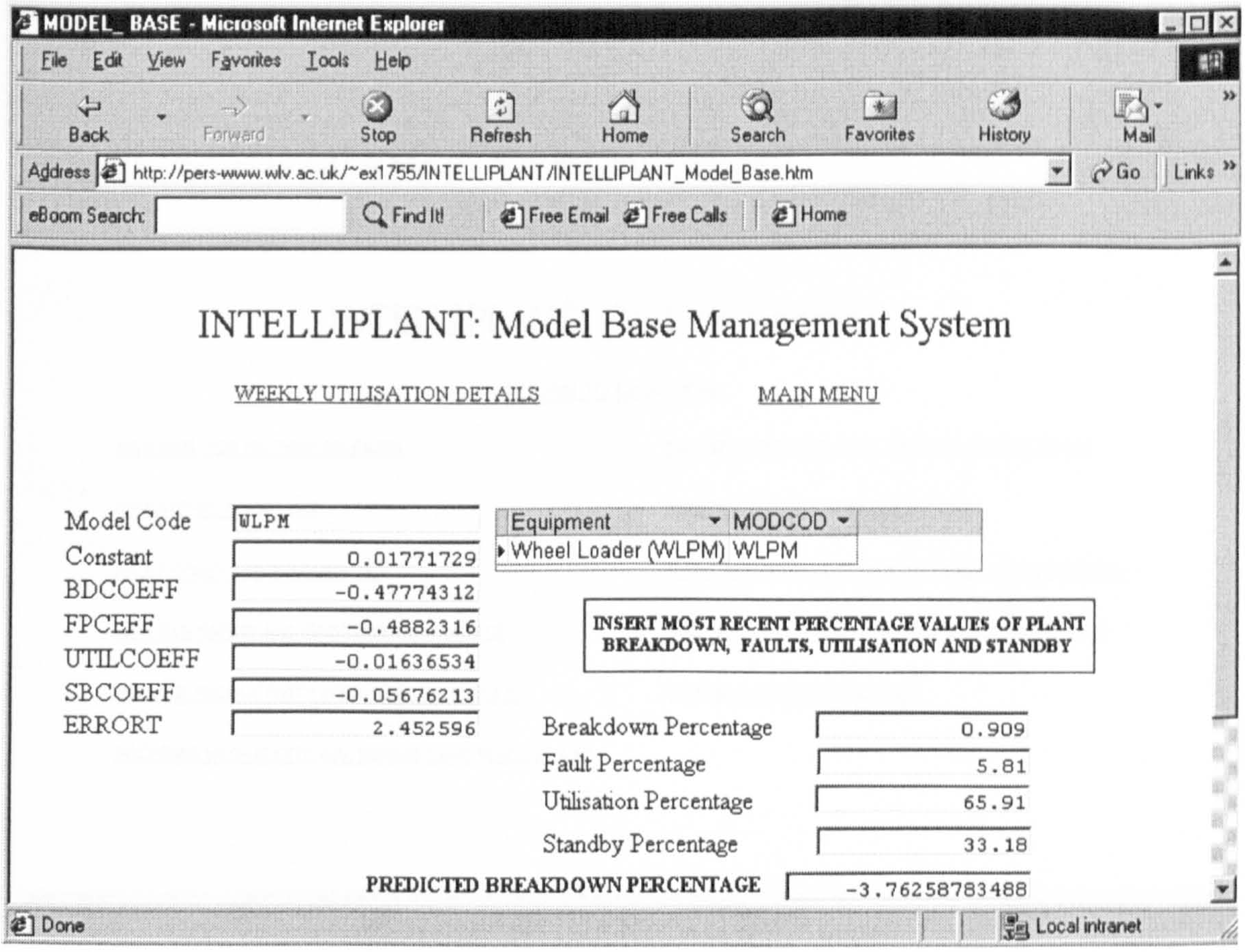
From the 'General Utilisation Details' page, users are then allowed to gain access to the actual details of the weekly utilisation records. The hyperlink <u>WEEKLY UTILISATION</u> enables this navigation. Figure 9.8 is a typical display of the 'Weekly Plant Utilisation Details' web page of INTELLIPLANT. The page enables the entry of the various utilisation details such as plant availability hour, breakdown hours, standby hours, etc in a particular week for a plant item. Based on this information, INTELLIPLANT automatically calculates and stores the respective percentages (i.e. percentage availability, percentage breakdown, etc) within the database.

Figure 9.8: INTELLIPLANT: On-Line Weekly Plant Utilisation Data Screen Display



From the web page displayed in Figure 9.8, users may also access the MBMS on-line. The MBMS web page displays the entire model coefficients for the four different plant items and the process logic section for plant breakdown prediction (Figure 9.9). The model library is also displayed as a means of cataloguing the models and their acronyms within INTELLIPLANT. Also, the MBMS web page allows users to query INTELLIPLANT for weekly prediction of plant breakdown based on extracted data from the 'Weekly Utilisation Details' page. Plant breakdown time as a percentage of projected plant availability is automatically calculated when the user prompts the system.

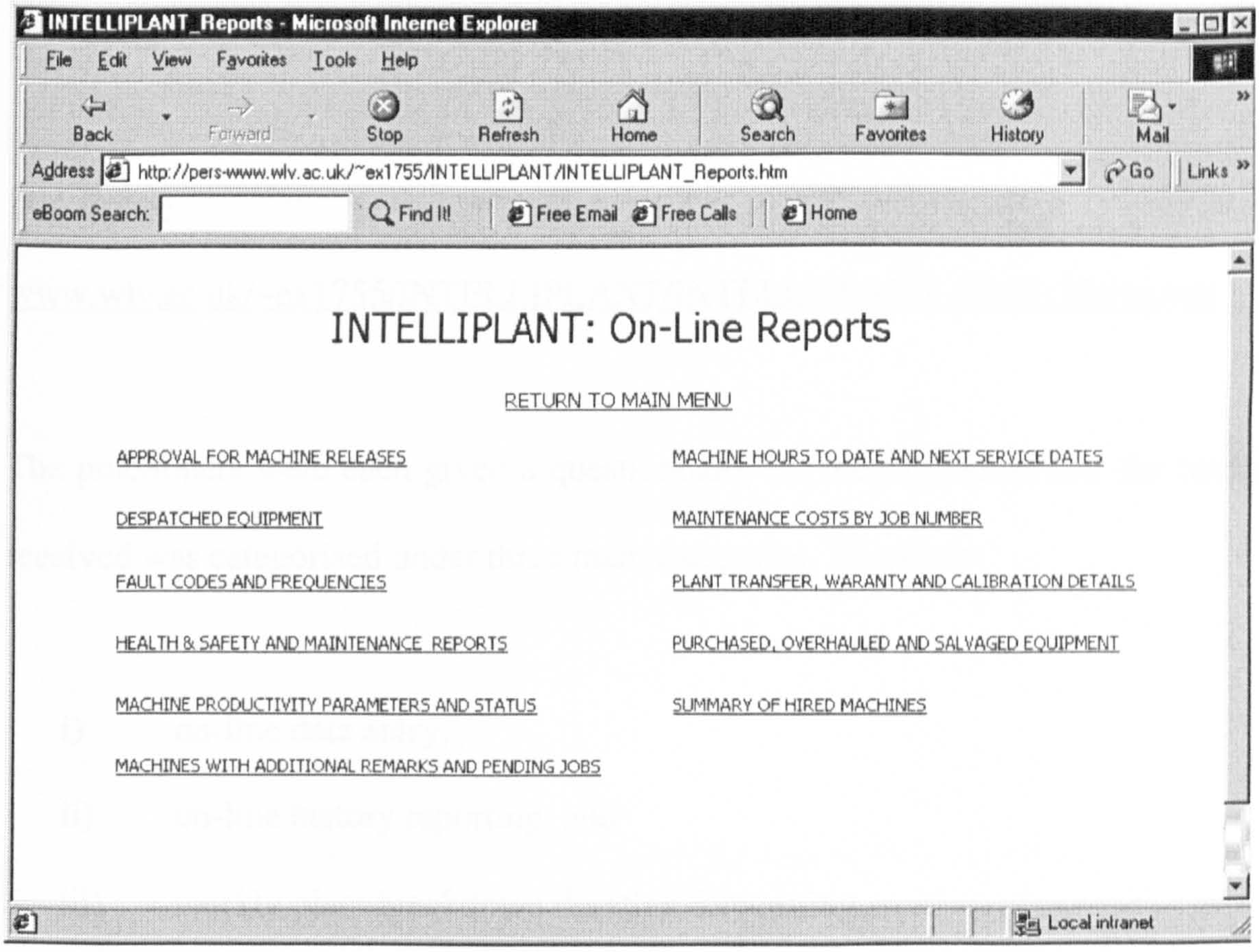
Figure 9.9: INTELLIPLANT: On-Line Model Base Management System Display



Once within the MBMS environment of INTELLIPLANT, the user may also navigate to the 'Weekly Utilisation Details' page or 'Main Menu' page by using the WEEKLY PLANT UTILISATION DETAILS and the MAIN MENU hyperlinks respectively.

The last GUI screen is the 'On-line Reports' web page. 11 links are included on the web page. These links provide access to 20 on-line reports relating to historical records of plant specifications, inventories and maintenance. Figure 9.10 is a typical illustration of the 'On-line Reports' web page. The page also allows access to the 'Main Menu' page through the RETURN TO MAIN MENU hyperlink.

Figure 9.10: INTELLIPLANT: On-Line Reports Display



PERFORMANCE EVALUATION

In order to evaluate the practical performance of INTELLIPLANT, five of the practitioners that had assisted during the pilot study/ data collection phases of the research were invited to participate in the evaluation.

For the purposes of the evaluation, a 'Demo' version of INTELLIPLANT was uploaded to the University of Wolverhampton staff website with URL:

http://pers-www.wlv.ac.uk/~ex1755/INTPLANTWEB.mdb

The practitioners were subsequently requested access the database and download a copy to their desktop (with the link C:\WINDOWS\DESKTOP\). Once a copy of the database was obtained, the users were then requested to access the INTELLIPLANT 'Main Menu' page through the URL:

http://pers-www.wlv.ac.uk/~ex1755/INTELLIPLANT/INTELLIPLANT_Main_Menu.htm

The practioners were each given a questionnaire for the evaluation and the feedback received was categorised under three main categories. These are:

i) on-line data entry;
ii) on-line history reporting; and
iii) weekly plant breakdown duration forecasting.

Feedback was also sought from an independent information research and solutions consultant in order to complement the feedback received from the practitioners. Sample copies of the questionnaire for the evaluation feedback and the correspondence with the independent consultant are included in Appendix V.

For on-line data entry, the performance criteria for the evaluation were centred on evaluating the ease with which users found INTELLIPLANT easy to navigate and also update with changes in historical records. For the on-line history file reporting evaluation however, the performance criteria were focussed mainly on the accuracy and the contents of the history file reports. The performance evaluation conducted to assess the forecasted weekly plant breakdown duration figures generally examined the working principles of the MBMS and also the accuracy of the forecasts produced by

On-Line History File Reporting

Practitioners were encouraged to evaluate the system by observing the reports generated on-line based on their plant history data posted to INTELLIPLANT. The procedure enabled a performance evaluation on the on-line reporting capabilities of INTELLIPLANT. All the practitioners gave positive recommendations about the report generation capabilities of the system. Although some recommended that the use of abbreviations for some of the table titles within the reports should be kept to a minimum. Such reports included: 'health and safety maintenance' and 'machines with additional remarks and pending jobs' reports.

Weekly Plant Breakdown Duration Forecasting

The final aspect of the performance evaluations sought to examine the practitioners' views on the plant breakdown forecasting capabilities of INTELLIPLANT. Based on feedback received, it was gathered that the practitioners found the GUI of the MBMS easy to interact with. They also commented on the fact that the models available for plant breakdown prediction were easy to select based on the plant type. However, the general consensus was that the number of models should be increased in future to enable a wider application of the forecasting capabilities of INTELLIPLANT. The highest ranking of this evaluation was 4 ('very good') from only one of the practitioners. The other four practitioners ranked the "Range of models provided within the MBMS" between 2 and 3 i.e. 'fair' and 'good' respectively (refer to Appendix V for the template). Under the 'general comments' they indicated interest in other off-highway plant types such as: telescopic handlers, bulldozers and dump trucks.

On the issue of accuracy of the predictions, the practitioners mentioned that the results obtained from INTELLIPLANT were reasonably close to the actually observed breakdown periods. On a scale of 1 to 5 (with 5 being excellent), 3 of the evaluators ranked the accuracy as 4, while the other two ranked the accuracy of the predictions as 3 (refer to template in Appendix V).

As part of the general comments the practitioners made in relation to the plant breakdown prediction capabilities of INTELLIPLANT, they also mentioned that the potential of the system in enhancing plant information management and decision support is very high.

SUMMARY

A description of the system integration technique, web hosting methodology and performance evaluation of the INTELLIPLANT has been given. INTELLLIPLANT was made web-enabled through the design and application of Data Access Pages. This made it possible for users to access individual, forms of a relational database through hyperlinked web pages from various locations. The web-enabled INTELLIPLANT system architecture was based on RDBMS and MBMS interface previously developed.

Typical practitioner case studies were utilised for the performance evaluation on the system. These were from collaborating organisations that were invited to participate in the performance evaluation exercise. The basis of evaluation included content, speed of connection, data entry, reporting and general decision support. Feed back received was categorised under three main categories. These are: on-line data entry; on-line history reporting; and weekly plant breakdown duration forecasting.

On the whole, the feed back on the performance evaluation were positive. These satisfactory performance mentioned by the practitioners ranged from data entry to on-line history report generation. On the issue of accuracy of the predictions, the practitioners also mentioned that the results obtained from INTELLIPLANT were reasonably close to the actual breakdown time observations. They also mentioned that the potential of the system in enhancing plant information management and decision support is very high.

However, a few of the feed back also highlighted area where INTELLIPLANT could benefit from improvements. These include:

i. the use of more pull down menus in order to avoid repeating details that were already contained on the RDBMS;
ii. minimising the use of abbreviations for some of the table titles within the reports;
iii. increasing the number of models in the MBMS to enable a wider application of the forecasting capabilities of INTELLIPLANT to other plant types.

CHAPTER TEN: Conclusions and Recommendations

INTRODUCTION

A review of the aim and objectives of this research is hereby made. The review enabled an assessment of the level of fulfilment of each objective. The assessment results indicated that the objectives of the study were reasonable realised. It also pointed out areas whereby additional work may be required in the future. Furthermore, in order to summarise the steps take to realise these objectives, a comprehensive review of each section of the work was also conducted in addition to the assessment of the research aim and objectives.

Commencing with the literature review, findings from this research exposed the need to improve off-highway plant information management. A generic approach to the research methodology was therefore conceived and implemented. The approach consolidated on the literature review findings and also the results from a pilot study. These two elements provided the framework upon which the other stages of the INTELLIPLANT were developed. As distinct contributions, the literature review provided information on the research needs and a theoretical framework, while the pilot study facilitated the process of acquiring on-site forms and actual historical data for the development. The pilot study also helped to harness the opinions of the practitioners through various interviews.

The RDBMS and MBMS were considered essential components of INTELLIPLANT. The RDBMS was developed based on established database systems development methodology, while the MBMS was developed as an assemblage time series models for predicting plant breakdown events. These were developed thorough a rigorous analytical procedure and validated using hold out samples and other appropriate statistical techniques. Hence, INTELLIPLANT emerged as an integrated system of a web-enabled RDBMS and MBMS both resident on a Microsoft Access 2000 platform.

Practitioners were then invited to test the prototype system and very useful feedback was received about the benefits of the system. The various issues raised in connection with possible improvements to INTELLIPLANT were also critically appraised as part of this performance evaluation. The concluding remarks from all aspects of the research are hereby presented. This chapter also presents the overall contributions and relevance of this research to industry practice.

AN ASSESSMENT OF THE FULFILMENT OF THE AIM AND OBJECTIVES

This research had aimed to substantially improve off-highway plant information management through the development of INTELLIPLANT. In the overall assessment it is concluded that this aim has been achieved through a systematic implementation of the research. Four cardinal objectives were defined in order to realise the aim of the research. A statement and an assessment of each objective is presented as follows:

OBJECTIVE 1: *To review relevant literature associated with off-highway plant information management science.* Existing methodologies and techniques relating to off-highway plant information management were comprehensively reviewed. The outcome of this objective led to the subsequent development of a strategy for improving these systems as envisaged.

OBJECTIVE 2: *To collect plant history file data and data capture mechanisms from various sources such as plant manufacturers, plant users and other practitioners.* This was achieved through the administration of questionnaires, telephone interviews, site visits and e-mail enquiries. A substantial amount of plant history forms and historical (quantitative) data was collected through the survey letters and questionnaires, while the site interviews facilitated the collation of qualitative data. As set out at the onset of the research, these data formed the basis upon which both the data capture/reporting (RDBMS) and parameter (breakdown) prediction (MBMS) components of INTELLIPLANT were designed.

OBJECTIVE 3: *To model, analyse and validate plant breakdown data collected using deterministic analysis techniques.* As a means of fulfilling this objective, an extensive procedure involving: historical data synthesis, exploratory analysis and final time series analysis of the collected data was vigorously pursued and achieved. The historical data synthesis exposed the plant items that were eventually selected for further analysis. It also facilitated a means of understanding the data sets and the inter-relationship between each of the parameters such as maintenance costs, fault occurrence, plant utilization and plant breakdown. The exploratory analysis led to the evaluation of four optional cases by which the plant breakdown prediction models could be developed. One of the cases, which had four independent variables (the lagged BDPERC, FLTPERC, SBPERC and UTILPERC), was eventually selected. The procedure was then adopted during the final time series analysis procedures on the plant history datasets for other plant items. Model validation was achieved through the utilisation of a 'hold out' sample, ANCOVA, ANOVA and non-parametric methods. The MAD and RMSE for each model (in addition to assessing the closeness of prediction to the actually observed) was also conducted as a means of validation the models.

OBJECTIVE 4: *To develop an 'intelligent' web-based plant information system for plant users.* The system developed incorporates validated report sheets on plant history and plant breakdown prediction models developed during the research. This objective was realised through the integration and web hosting of the RDBMS and the MBMS. The RDBMS was made web enabled through data access pages through which plant history data could be posted onto INTELLIPLANT from remote locations. Also, apart from having the capability of generating several on-line history reports, the information system has the capability to predict off highway plant breakdown percentage through the validated models of its MBMS.

A summary of the major conclusions from all phases of the development of INTELLIPLANT is hereby presented. The summary examines findings from the: literature review; pilot study/system development methodology; the RDBMS design; descriptive analysis of historical data; exploratory time series analysis; the MBMS development; system integration; and the web hosting and performance evaluation phase.

CONCLUSIONS FROM THE LITERATURE REVIEW

Findings from the literature review revealed that the three categories of plant information management systems currently in existence do not have the capacity to adequately support the dynamic requirements of modern off-highway plant information management. Several limitations account for this inadequacy, four of these were most notable. First, the systems are not easily accessible from remote plant locations. Second, there tends to be an over reliance on the database manager. Third, the reports generated often required lengthy mathematical manipulations. Fourth, the existing Internet based systems were mostly informative in nature.

In order to set the off-highway plant sector in proper context, IT applications in similar industries such as aircraft, shipping, railways and roads were reviewed. Results showed that these that these industries have since adopted intelligent web-based information management technologies that significantly enhanced their operations. These web-based systems reduce problems of accessibility to the system and therefore allow ease of database update from various locations. When compared with the off-highway plant sector, these other industries were more advanced in terms of information management. The need to develop a web-based tool for off-highway plant was therefore established.

CONCLUSIONS FROM REVIEW OF INTELLIGENT WEB BASED SYSTEMS

Three-tier web based client-server architectures have been proven to provide a suitable hosting platform for intelligent information systems The first and second tiers accommodate the user interface and the broker server respectively. The third tier hosts the 'intelligent' components, which include a: web-enabled RDBMS, MBMS and/or a KBMS.

From the review of developments in intelligent web-based information systems, it was inferred that the development of an intelligent web based off-highway plant information management system would be advantageous. The system should also be based on three-tier architectures. This was because, the RDBMS allowed the dynamic modelling of historical records and this was a major advantage over existing information management systems. Traditionally, the existing systems had been modelled on fixed historical data. Also, the MBMS contains routine and special quantitative models that provide the analysis capabilities of the intelligent system. This potential enabled the prediction plant breakdown, model faults and other plant parameters based on the dynamic plant history database.

CONCLUSIONS FROM PILOT STUDY AND SYSTEM DEVELOPMENT STRATEGY

The adopted generic approach to this research methodology led to a two-component research structure. The first component was a literature review and the second component was a process that combined theory formulation, testing and integration. Having conducted a thorough literature review as first component, the second component was divided into seven (sub-component) stages. These were the: pilot study; RDBMS design; data synthesis and selection of modelling technique; exploratory analysis of plant history data; MBMS design, component integration and web hosting; and system validation and testing.

The pilot study (which was the first stage) was undertaken with the aim of identifying the shortcomings inherent within existing systems and also determining the practitioner requirements. Data collated under the pilot study were classified into two broad categories i.e. the plant information management forms and history category and practitioner/industry requirements category. These categorisations enabled data capture within the applicable contexts of the proposed system development.

The limitations of paper documentation and the cost of purchasing and operating software and associated hardware requirements were discovered to be major factors affecting the efficient utilisation of current plant information management systems. Also, practitioners sought a system which could automate the prediction of plant breakdown events in addition to its being able to produce reports of inventories, maintenance records, specifications and plant historical costs. These findings therefore, formed significant criteria upon which INTELLIPLANT was conceptualised. INTELLIPLANT overcomes these limitations as it can be utilised by owners of existing standard office applications such as Microsoft Access 2000. Also it can be viewed from any computer with a standard web browser such as Internet Explorer, hence requiring no additional software.

CONCLUSIONS FROM THE RDBMS DESIGN

A RDBMS was selected due to its advantages over the hierarchical and network database structures. This selection was based on an evaluation of the properties of each structure type in line with the technical objectives of the INTELLIPLANT.

The designed RDBMS was ensured to facilitate the documentation of inventories of plant and stock items. Effective maintenance management was also assured through the generation of real time history reports. These reports covered plant specifications, daily breakdown summaries within the entire fleet and daily time sheets. Also included were plant maintenance real time status, servicing and maintenance records and schedules, site fitters' daily record and weekly worksheets amongst others.

The schema of the RDBMS was formulated based on an E-R modelling technique and a normalisation of datasets. Input and output forms and reports were thus subsequently evolved from the final E-R model using the Microsoft Access 2000 software. The form navigation and report generation capabilities of the RDBMS were greatly enhanced by the application of macros and SQL programming of the RDBMS. The reports designed were based on queries developed using SQL. About 25 queries were developed to enable INTELLIPLANT generate real time plant history report sheets. The RDBMS system also provided a means of interface with the MBMS.

CONCLUSIONS FROM THE DESCRIPTIVE ANALYSIS OF HISTORICAL DATA

The descriptive analysis of the historical data conducted facilitated a clearer understanding of plant performance parameters. The significant effect of plant breakdown time on general plant performance was demonstrated. Results show that plant utilisation, maintenance and costs are drastically affected by the incidence of plant breakdown. From the frequency statistics, plant breakdown accounts for about 7 percent of total plant availability time (in the absence of plant standbys). This percentage (although would vary depending on plant age and working conditions) could reduce plant production rates significantly. It was therefore considered important to model this 'breakdown' phenomenon.

This study acknowledged the several contributions that had been made in determining the best means of modelling off-highway plant parameters. Such studies had aimed at utilising plant history records to model some plant performance parameters. However, this study focussed on developing plant breakdown prediction models in order to contribute to research efforts and enhance off highway plant information management.

In selecting an appropriate modelling technique, the merits and demerits of available options were reviewed. The reviewed techniques include: neural computing (artificial neural networks), genetic algorithms (and hybrids of ANN and GA), fuzzy logic and time series analysis. The time series technique was selected because the method can determine the effect of 'outside events'. Furthermore, the method developed by Box and Jenkins was also proposed for building the proposed breakdown prediction model.

CONCLUSIONS FROM THE EXPLORATORY TIME SERIES ANALYSIS

An exploratory time series analytical procedure led to the identification of the ARIMA process as most suitable for the plant breakdown prediction model development. After a rigorous analysis using the SPSS trends (version 10) software, an ARIMA (1,1,0) model was identified. This model (developed for wheel loaders) was used in an estimation procedure in which four separate cases of combinations of the independent variables, i.e. the lagged BDPERC, FLTPERC, UTILPERC and SBPERC were analysed via the ARIMA process. Case IV (that had the combination of the four independent variables) was selected due to closeness of its prediction to the actual value of BDPERC.

The method used in the exploratory investigation was thus considered suitable for analysing the historical data on other plant items such as hydraulic tracked excavators, backhoe-loaders and off-highway haulers. This process culminated into the model library development of INTELLIPLANT MBMS.

CONCLUSIONS FROM THE MBMS DEVELOPMENT

The development of the BDPERC models for the MBMS involved a three-part simulation namely; a review of the historical data for the selected plant item; a time series analytical procedure based on the methodology established under the exploratory study; and model development/ validation process.

As a means of validating the predictive capabilities of the models, the MAD and the RMSE calculations were conducted. Also, the (ANOVA) technique was used to facilitate a procedure of testing the statistical significance of the combined variables: the lagged BDPERC, FLTPERC, UTILPERC and SBPERC on the predicted results. The MAD ranged between 5.34 and 11.07 percent for the wheel loader and off-highway hauler prediction models respectively. The RMSE values also showed similar trends with the off-highway hauler prediction model yielding the highest value of 29.79 per cent. However, it was also observed that the range of actual BDPERC values was highest for the off-highway loaders. A situation, which signified that the predictive capabilities of the models could become weaker as the range of observed BDPERC increases.

The MBMS of INTELLIPLANT was, therefore developed as a system containing a library of the validated time series models, which can enhance the prediction the plant breakdown percentage time. The MBMS development followed a four-step methodology. These were: the definition of the information/process logic structure of the MBMS; the creation of the model base and directory; the definition of the SQL *syntax and computational logic used for the model management; and the establishment of the model execution procedure.*

CONCLUSIONS FROM THE SYSTEM INTEGRATION, WEB HOSTING AND PERFORMANCE EVALUATION

INTELLLIPLANT was made web-enabled through the design and application of Data Access Pages. The system therefore became accessible to users for the accessing of individual forms of the relational database through hyperlinked web pages from various locations. The web-enabled INTELLIPLANT system architecture was based on RDBMS and MBMS interface previously developed.

Typical practitioner case studies were utilised for the performance evaluation on the system. These were from collaborating organisations that were invited to participate in the performance evaluation exercise. The basis of evaluation included content, speed of connection, data entry, reporting and general decision support. Feed back received was categorised under three main categories. These are: on-line data entry; on-line history reporting; and weekly plant breakdown duration forecasting.

On the whole, the feed back on the performance evaluation were positive. These satisfactory performance mentioned by the practitioners ranged from data entry to on-line history report generation. On the issue of accuracy of the plant breakdown predictions, practitioners also expressed that the results obtained from INTELLIPLANT were reasonably close to the actual breakdown time observations.

An evaluation of the practitioners' feedback revealed that the potential of the system in enhancing plant information management and decision support is very high.

OVERALL CONTRIBUTION TO RESEARCH AND PRACTICE

Prior to the development of INTELLIPLANT, off-highway plant information had depended extensively on paper-based documentation of plant history records. Various plant users had also used some manufacturer software as stand alone systems. Such programmes could do either of several things such as the evaluation of equipment alternatives, specification information and other information.

However, the introduction of INTELLIPLANT provides an integrated environment, which provides users with an enhanced environment for the collation and manipulation of plant history records. Also, the capability of the system to predict plant breakdown percentage time from plant history records is a significant contribution to off-highway plant information management.

The findings from this research have also opened up new grounds in off-highway plant information research. The research findings present an innovative approach to plant breakdown prediction based on plant items using the ARIMA process. This complements several efforts to model this phenomenon to date. Finally, the outcome of this research has also enabled a systematic capture of plant history data. With continued industrial application, these data would be useful for the development of further research in this field.

OVERALL CONCLUSION

The development of INTELLIPLANT has proven to be a worthy and novel contribution to off-highway plant information management. The derived ARIMA (1,1,0) models (and their applications in INTELLIPLANT) are both useful and accurate predictors of plant breakdown time. Practical model application is now required since this will enhance plant management on projects that require extensive and continuous plant usage. Plant maintenance management requires adequate forecasts of the likelihood of breakdowns, even when standard preventive maintenance management procedures are strictly adhered to. However, the implementation of preventive maintenance programmes often causes plant managers to dither regards when to, and when not to service equipment. Better decision support would now be assured as a result of the application of INTELLIPLANT.

RECOMMENDATIONS AND ASPECTS FOR FUTURE WORK

Nevertheless and despite the aforementioned benefits of INTELLIPLANT, it is necessary to highlight that this study has been limited in a number of aspects. For example, a far greater quality and quantity of plant history data would facilitate subsequent analyses. Unfortunately, poor history file information predominates within the plant and equipment sector; a finding previously highlighted in various research work.

Also, this study has considered the incidence of fault occurrence, utilisation, standby, and breakdown percentages as predictor variables and has given satisfactory results. However, additional work that utilises the findings emanating from this research and other similar studies may yield the development of more robust plant breakdown prediction models. For instance, models that could also consider the influence of plant operators, machine specifications, operating environment etc. as additional predictor variables. The system's decision support capabilities may also be improved through the development and integration of a knowledge base system.

Finally, as part of future enhancements proposed for the improvement of the GUI of INTELLIPLANT, the following aspects mentioned by the practitioners should be implemented: the use of more pull down menus; minimisation of abbreviations contained in the report tables; and the increase of the number of models in the MBMS to cover other plant types.

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APPENDIX

APPENDIX I: Correspondence with Organisations

4th January 2000

Dear Sir,

Re: Request for Information on Plant Data

I am currently undertaking research that aims to improve plant history information management here at the Built Environment Research Unit, School of Engineering and the Built Environment, University of Wolverhampton, under the guidance of Dr David Edwards. Specifically, the research will develop web-based plant management software that will be available to collaborating plant users free of charge. One of the software's features will be the incorporation of management control mechanisms that will accurately predict plant productivity and/or maintenance costs by users.

In order to realise this work, a pilot study seeks to collate typical record formats used by plant users (e.g. inventories, maintenance records, maintenance and purchase costs, health and safety reports and so forth) as a basis for the software's development. In this way the software will represent a system designed by industry for industry.

With the previous in mind, would your company be willing to assist with the research outlined above? Ideally, sample copies of records held as well as general guidance and constructive comment are sought. Please note that all information will be treated with strict confidentiality and that collaborators will be entitled to free access to the research findings as they unfold.

We thank you for your anticipated co-operation and look forward to your response in due course. Please feel free to contact me if you require further information.

Yours Faithfully,

David Oloke
Doctoral Researcher
The Plant Management Research Group
Built Environment Research Unit
School of Engineering and the Built Environment,
University of Wolverhampton, Wulfruna Street,
Wolverhampton, WV1 1SB, UK
Tel: 01902 322156; Fax: 01902 322743
e-mail: d.a.oloke@wlv.ac.uk

Return-path: <in6365@wlv.ac.uk>
Envelope-to: D.A.Oloke@wlv.ac.uk
Delivery-date: Tue, 06 Feb 2001 10:43:29 +0000
X-Sender: in6365@wlv.ac.uk
Date: Tue, 06 Feb 2001 10:41:30 +0000
To: simon.day@lafarge-ukaggregates.lafarge.com
From: "Dr David J. Edwards" <in6365@wlv.ac.uk>
Subject: Re: Mobile Plant Study
Cc: D.A.Oloke@wlv.ac.uk

Simon

Thank you and Mr John Close for your invaluable help and support. David and myself will contact the managers of these aforementioned sites shortly to arrange a mutually convenient time and date for our meeting.

Once again, many thanks and best wishes

David
PS. please forward my regards to Graham

At 20:14 05/02/01 +0000, you wrote:
>
>David,
>
>Apologies for the late reply.....I have had quite a hectic last few weeks.
>
>I have spoken to my boss (John Close - Production Director) and he is happy
>for us to co-operate with the study.
>
>I presume you wish to visit a few sites to collect examples of data - I
>have selected 3 sites on the basis of proximity to Wolverhampton and
>perhaps more importantly, access to a photocopy machine ! All these sites
>are in my old area and are now under the control of Graham Glasson (Area
>Operations Manager).
>
>Alrewas Quarry (Alrewas, Burton-on-Trent, Tel 01283 791220, Manager Len
>Mudd)
>
>This is a 500kt pa sand and gravel unit with the folowing mobile plant : 1x
>Volvo A30 dumper, 1x Volvo A35, 1x Volvo 36t hydraulic excavator, 1x
>Komatsu loader - equipment is serviced and maintained by OEM agents.
>
>Llynclys Quarry (Llynclys, Oswestry, Tel 01691 831700, Manager Keith
>Haystead)
>
>This is a 450kt pa limestone quarry and operates : 1 x Terex 45t dumper, 1
>x Aveling Barford 35t, 1x Barford 30t, 2 x cat 966 shovels, 1x Liehbherr
>954 Hydraulic Shovel. - equipment is serviced by Lafarge Aggregates site
>staff.
>
>Graig Quarry (Llanarmon-yn-Ial, Ruthin, Tel 01824 780 653, Manager
>Richard Sanderson)
>
>This is a 600kt pa limestone quarry and operates : 1x Barford 55t dumper,
>1x Barford 40t dumper, 1x cat 50t dumper, 1 x Volvo L330 shovel, 2 x
>Komatsu shovels. - equipment is serviced by on site sub-contractor.
>
>
>Please feel free to contact some or all of them directly to arrange a short
>visit - I will let them know to expect a call. Obvoiusly they are all busy
>people but I am sure they will be able to find the time to assist.
>
>I am away on leave until 14th Feb. If you require any further information
>please call me after this date.
>

UNIVERSITY OF WOLVERHAMPTON

FAX MESSAGE

DATE: 25/07/01

To: Mr. Keith Haystead, Lafarge Aggregates
Fax No: 01691830773

From: Mr. David Oloke, Wolverhampton University
Fax No: 01902322743

SUBJECT: Thanks

Dear Keith,

Good day to you. Just to say thanks for the warm reception accorded us at your offices yesterday.

The visit was quite educative and beneficial. Information we collected on-site has helped us to greatly consolidate on the findings of the on-going study.

We were also pleased to have been introduced to the recently acquired computer software for managing plant history records and reports. It is our understanding that full access to every aspect of the programme can only be through your good self. We are therefore hoping to arrange for a similar meeting in the near future to enable us review the software again together. I will be calling you sometime soon to finalise details, as it may be convenient for you.

Please express our gratitude to Lynda, Paul and Matt and all the site staff who assisted us during the visit.

Regards,

David

TEXT BOUND INTO

THE SPINE

Return-path: <MA.Taylor@napier.ac.uk>
Envelope-to: D.A.Oloke@wlv.ac.uk
Delivery-date: Thu, 11 Jan 2001 13:16:15 +0000
From: "Taylor, Mark" <MA.Taylor@napier.ac.uk>
To: 'David Oloke ' <D.A.Oloke@wlv.ac.uk>
Subject: RE: Bauma 2001
Date: Thu, 11 Jan 2001 13:12:18 -0000

Dear David,

Thanks for your reply. E-groups are great, but I am always very careful with providing, those who appear to be too interested with, specific details. Please be carful, as not everyone in the academic world is as professional as you and I. I don't mean to sound a drag, but when you are in our situation you have to be careful.

Bauma 2001 (www.bauma.de) is a plant and machinery trade world fair held in Munich (Germany). It is attended by international machine manufacturers and buyers. You may get some valuable contacts from this web site. As part of an international travel scholarship I hope to attend this fair when I visit Germany in April. I'm sure that I'll collect loads of relevant info., so i'll collect a load for you.

My japanese friends are always more than willing to talk about their technology. Specific details are sometimes difficult to obtain, hence the reason I am trying to learn to speak and read japanese within my field (construction mechatronics). Before I give you any names, I would be grateful if you could have a good look at what is available on the internet. Look at the Big-Six web sites, e.g. Obayashi, Shimizu, Takanaka, Taisei, Kajima, Kumagai-Gumi. Also try Tokimec Construction Systems Inc., Komatsu,Honda, Hitachi, Mitsubishi, Fujitsu and other machine manufacturers.

I am writing a paper for the ICE at the moment. It gives specific details about some of the machines that I witnessed when I visitied Japan last year. Try and get a hold of the International Association of Automation and Robotic in Construction (www.iarc.org) Catalogue of Construction Robots. iaarc.org There is also similar book of Japanese systems, published by the Japanese Council for Construction Robot Research.

If you have any further questions please contact me via e-mail or 0131 455 2312. A lot of people have been helpful to me over the last two years and I am always willing to help and encourage other research students.

Speak to you soon

Mark Taylor

-----Original Message-----
From: David Oloke
To: Taylor, Mark
Sent: 1/11/01 12:55 PM
Subject: Re: Construction Plant & Machinery

Dear Mark,

I am so delighted to hear from you and to know that you have actually covered a of grounds on researching into automated technology in the construction industry.

My research is relatively at a newer stage but could benefit from your experience as I can gather from your mail. The main focus of the work is on
Construction Plant and Equipment. At the moment we are conducting a pilot

study which is collating any details on paper record formats and
available
software for managing construction plant data both here in the UK and
abroad.

To this effect, I shall appreciate your kind assistance in advising on a
list of contacts for such information; either as phone, fax, e-mail,
web-site or surface contacts. A list of your Japanese contacts relevant
to
this work will also be most welcome.

I am apparently not aware of Bauma 2001. Could you kindly send me the
web-site or any details you may have about it?

Thanks a lot. I shall definitely keep in touch.

Regards and best wishes,

David.

A.1. DEMOLITION LTD.

DEMOLITION AND DISMANTLING SPECIALISTS

EASTWAYS · WITHAM · ESSEX CM8 3YU
Tel: (01376) 515615 · Fax: (01376) 515616
www.a1demolition.co.uk · E-mail: admin@a1demolition.co.uk

Ref: CS/MM/Olike/2901 29th January 2001

31/1/01

F.A.O. Mr. D. Oloke
Doctoral Researcher
Plant Management Research Group
BERU, SEBE
University of Wolverhampton
Wulfruna Street
Wolverhampton, WV1 1SB.

Dear Sir,

Reference your letter dated 16th January 2001. We regret we are unable to help specifically as we do not have the type of information you are asking for.

We would suggest that you can obtain general information from our website as above and by direct link to The National Federation of Demolition Contractors site, www,nfdc.co.uk

Yours faithfully,

C.Smith

APPENDIX II: Organisations Contacted for Pilot Study

Appendix II: Names and Location of the Contacted Organisations

S/No.	Company Name	Location
1	Dave Lucey Ltd	Frome Somerset
2	Alpha Construction Ltd	Derby Derbyshire
3	Cooper Plant Hire & Civil Engineering	York North Yorkshire
4	M & E Civil Engineering & Groundworks Ltd	Kent
5	Story Construction Ltd	Carlisle Cumbria
6	Crilly Site Preparation	Newry County Down
7	Grant Construction Services (Fife) Ltd	Dunfermline Fife
8	J.U Bowen (Construction) Ltd	Newtown Powys
9	Ace Civil & Building Contractors	Glamorgan
10	E.P Clark & Co Ltd	Billingshurst West Sussex
11	Frank Lyons Group	Dunmow Essex
12	McLaughlin & Harvey Ltd	Newtownabbey County Antrim
13	Brett Construction Ltd	Canterbury Kent
14	Corr Brothers	Retford Nottinghamshire
15	Reliable Construction Co.Ltd	Ellesmere Port
16	Tangent Construction Ltd	Hartlepool Cleveland
17	SCD Construction Ltd	Leeds West Yorkshire
18	Moorland Civil Engineering & Plant Hire	Stockport Cheshire
19	McArdle Civil Engineers & Technical Services	Reigate Surrey
20	Dewsbury Civil Engineering Co.Ltd	Bury St. Edmunds Suffolk
21	Mutleys Plant Services	Dover Kent
22	DDT Engineering Ltd	Braintree Essex
23	Masterhitch Europe Ltd	Rochester Kent
24	Bitmen Products Ltd	Cambridge Cambridgeshire
25	Rapid International Ltd	Craigavon County Armagh
26	Construction Spares & Engineering International Ltd	Nottingham Nottinghamshire
27	Lloyd Loaders (MH) Ltd	Halifax West Yorkshire
28	Komatsu UK Ltd	County Durham

Appendix II: Names and Location of the Contacted Organisations (Cont'd)

S/No.	Company Name	Location
29	Colton Machinery	Nuneaton Warwickshire
30	Case UK Ltd	Hook Hampshire
31	Bx Plant Sales	Chichester West Sussex
32	Autoguide Equipment Ltd	Salisbury Wiltshire
33	Thomas Equipment UK	Rossendale Lancashire
34	Excel Plant Hire Ltd	London
35	Hiremasters Ltd	London
36	Langshield Plant & Haulage Ltd	London
37	Ever Ready Equipment Hire Ltd	London
38	Maxxiom Ltd	London
39	Marron Civil Engineering Ltd	London
40	Finchley Plant Hire	London
41	P Kilganon	London
42	Kayleigh Plant Hire Ltd	London
43	Southern Groundworks	London
44	Miskin Plant & Tool Hire (London)	London
45	Network Plant Ltd	London
46	H.E Services (Plant Hire) Ltd	London
47	Universal Aerial Platforms Ltd	London
48	Ranger Plant Hire (SE) Ltd	London
49	Kier Plant	London
50	Tilbury Douglas Construction Ltd	Birmingham
51	Tilbury Douglas Construction Ltd	Mansfield Nottinghamshire
52	Tulloch Construction Group Ltd	Glasgow Lanarkshire
53	Mansell Construction Services Ltd	Derby Derbyshire
54	Balfour Beatty Construction Ltd	Pontefract West Yorkshire
55	Lovell Construction Ltd	London
56	Austick Construction Ltd	Cramlington Northumberland
57	DSM Demolition Ltd.	Heartlands Birmingham
58	Al Demolition Ltd	Chemlsford
59	Excavation & Contracting (UK) Ltd.	Denton Manchester
60	Controlled Demolition Group Ltd	West Yorkshire

APPENDIX III: Sample Plant History Forms

VOLVO

Volvo Construction Equipment GB Ltd

Engineer's Report: Service Work Record

Engineer J FLITNEY	Clock no. 384	Customer order no.
Job no. 1057201		Machine type EC240LC
Date 25/5/00		Machine hours 550
Customer Fox Plant		Serial no. 03016
Location Leighton Buzzard		Engine no.

Instructions received/Fault reported ① Wiper linkage ② Boom judder ③ Radio

Labour category	☐ Workshop	☐ Field	**Travel time to site**	Start 730	Stop 800
	☐ Spraying	☐ Welding	**Return travel time**	Start 2000	Stop 2030
			Total mileage	30mls	

Work description

① Removed covers etc, found wiper link bar had come adrift from wiper spindle. Refitted link bar and tested. All working ok refitted covers.

② Replaced boom circuit shock valve

③ Swopped radio & arial in attempt to get decent reception on AM FM perfect. Still no change even with parts swopped so refitted old parts.

Start 800	Stop 2000	Break
Function code 80	Debit code	
Part no.		
Start	Stop	Break
Function code	Debit code	
Part no.		
Start	Stop	Break
Function code	Debit code	
Part no.		
Start	Stop	Break
Function code	Debit code	
Part no.		
Start	Stop	Break
Function code	Debit code	
Part no.		

The above work has been carried out to my/our satisfaction. Times of arrival and departure are correct.

The repairs detailed on this sheet have been carried out and inspected by Volvo personnel.

Notes: In the case of an excavator this does not effect an owner's statutory obligation to have a valid certificate of thorough examination.

Machines are driven at owner's risk.

Customer's signature

Job completed?	Yes	No
Machine usable on leaving site?	Yes	No
Awaiting parts?	Yes	No
Parts returned?	Yes	No
Customer to dispose of waste oil/fluids?	Yes	No
Waste oil/fluids removed by Volvo?	Yes	No

Engineer's signature

J Flitney

F203 issue 4

White: Work Record Pink: Personnel Yellow: Customer Green: Engineer

Volvo Construction Equipment Europe Ltd

Engineer's Report: Service Work Record

Engineer G. TURNBULL	Clock no. 189	Customer order no.	
Job no. 3-34701		Machine type	EC140
Date 30-11-00		Machine hours	907
Customer LOMOND PLT		Serial no.	3030
Location CROY		Engine no.	

Instructions received/Fault reported

HYD LEAK

Labour category			Travel time to site	Start 12.00	Stop 12.30
	Workshop	☑ Field	Return travel time	Start	Stop
	Spraying	Welding	Total mileage	17	

Work description	Start	Stop	Break
Check & repair hyd leak at hyd pump area. Run & test OK	Start 12.30	Stop 13.30	Break
	Function code 90000	Debit code 01	
	Part no.		
	Start	Stop	Break
	Function code	Debit code	
	Part no.		
	Start	Stop	Break
	Function code	Debit code	
	Part no.		
	Start	Stop	Break
	Function code	Debit code	
	Part no.		
	Start	Stop	Break
	Function code	Debit code	
	Part no.		

The above work has been carried out to my/our satisfaction. Times of arrival and departure are correct.

The repairs detailed on this sheet have been carried out and inspected by Volvo personnel.

Notes: In the case of an excavator this does not effect an owner's statutory obligation to have a valid certificate of thorough examination.

Machines are driven at owner's risk.

Customer's signature

Job completed?	Yes	No
Machine usable on leaving site?	Yes	No
Awaiting parts?	Yes	No
Parts returned?	Yes	No
Customer to dispose of waste oil/fluids?	Yes	No
Waste oil/fluids removed by Volvo?	Yes	No

Engineer's signature G Turnbull

F203 issue 4

White: Work Record Pink: Personnel Yellow: Customer Green: Engineer

Volvo Construction Equipment GB Ltd
Duxford, Cambridge
CB2 4QX

Telephone 01223 836636
Telefax 01223 837273
Registration No. 1673954 England
Registered Office Duxford, Cambridge CB2 4QX

VOLVO

Volvo Construction Equipment GB Ltd

Engineer's Report: Service Work Record

Engineer J FLITNEY	Clock no. 384	Customer order no.	
Job no. 1057201		Machine type	EC240LC
Date 19/5/00		Machine hours	530?
Customer Fox Plant		Serial no.	03016
Location Pratts Quarry		Engine no.	

Instructions received/Fault reported

Bucket rolling out. slow hydo / Judder on hydo. (Intermittant)

Labour category		Travel time to site	Start	Stop
☐ Workshop	☐ Field	Return travel time	Start 1730	Stop 1800
☐ Spraying	☐ Welding	Total mileage	15mls	

Work description Checked m/c pressures
Found to be 320BAR
Worked m/c with gauges connected
found that he was working m/c
right on the max ~~to~~ pressure. Suspect
faulty shock valve's causing the
problem as I have already swopped
the bucket over with the boom to
stop the bucket rolling out when
m/c was new.
Ordered parts for repairs

Start 530	Stop 730	Break
Function code 90	Debit code	
Part no.		
Start	Stop	Break
Function code	Debit code	
Part no.		
Start	Stop	Break
Function code	Debit code	
Part no.		
Start	Stop	Break
Function code	Debit code	
Part no.		
Start	Stop	Break
Function code	Debit code	
Part no.		

The above work has been carried out to my/our satisfaction. Times of arrival and departure are correct.

The repairs detailed on this sheet have been carried out and inspected by Volvo personnel.

Notes: In the case of an excavator this does not effect an owner's statutory obligation to have a valid certificate of thorough examination.

Machines are driven at owner's risk.

Customer's signature

Job completed?	Yes	No
Machine usable on leaving site?	Yes	No
Awaiting parts?	Yes	No
Parts returned?	Yes	No
Customer to dispose of waste oil/fluids?	Yes	No
Waste oil/fluids removed by Volvo?	Yes	No

Engineer's signature J Flitney

F203 issue 4

White: Work Record Pink: Personnel Yellow: Customer Green: Engineer

Volvo Construction Equipment GB Ltd
Duxford, Cambridge
CB2 4QX

Telephone 01223 836636

Telefax 01223 837273

Registration No. 1673954 England

Registered Office Duxford, Cambridge CB2 4QX

0 97220 - 30160

SERVICE HISTORY

~~3030~~ 3034701

LIMINARY INVOICE
CENTRAL WARRANTY - VOLVO
COMPANY
ACCOUNT

COA-1240003602

152010010938

****

Page 1

VOLVO STIRLING

Tax date	0/00/00
Workshop order	3034701
Original WS-Ord	
Customer	000180
Sales model	EC140LC
Serial number	03030
	907
Customer refere	WARRANTY IM0190
	7323-1

eration	Quantity	Price/unit	Value	
BOUR	1.00	30.55	30.55	2090
AVEL MILES	17.00	.65	11.05	2090
AVEL HOURS	.50	30.55	15.27	2090
	Net value		56.87	
	Total value		56.87	

ULT: HYDRAULIC OIL LEAK
USE: O-RING LEAKING AT HYDRAULIC PUMP
TION: REPLACED O-RING

SAP385A ORDER HEAD 001 1/06/00 11:49:23

r type 1 WS on machine Status 400 SP Ord/Pick & mech reprt in progr.

rder 1057201 Created 190500 15.52 Started 190500 15.30 Rep dat 250500

onsible ROY BRIGHT Responsible depot 001

anics 384 J Flitney

omer 000180 CENTRAL WARRANTY - VOLVO
FOX PLANT (OWMBY) LTD
CAENBY HALL
CAENBY CORNER
MARKET RASEN
LINCOLNSHIRE

LN8 2BU

it YES External NO

site FOX PLANT PRATTS QUARRY

ready Invoice fee _ Miscellaneous B 3 % .00

ref

s model EC240LC Serial number 03016

s Env code 130 Deliv date 150200 Brand KOF

SW
rks CW CCP2B W2
GA
SA CCPI

lem RECTIFY NO POWER ON LIFT & BUCKET ROLLING OUT Serv exchange
ription Quantity
0

04 1000 - 10160

APPENDIX IV: Database Attribute List

APPENDIX IV: Details of Codes used in the ER Model

Plant Inventory Code

Attribute	Code
Machine Code	MCHCOD
Machine Type	MCHTYP
Model Type	MODTYP
Site Code	STCODE
Initial Purchase Costs	PURCOS
Date of Machine Purchase	BUYDTE
On Hire?	ONHIR?
Hire Period	HIRPRD
Hire Rate	HIRRTE
On Transfer?	ONTRN?
Origin	ORIGIN
Destination	DESTNT
Movement Date	MOVDTE
Reject Plant?	REJECT
Date Rejected	DTEREJ
Current Plant Status	PLTSTS
Breakdown Hours	BDNHRS
Machine Hours	MACHRS

Stock Inventory

Attribute	Code
Date	SIDATE
Job Number	JOBNUM
Part Number	PRTNUM
Item	ITDESC
Unit Cost	UNCOST
Total Cost	TTCOST

Specification

Attribute	Code
Machine Code	MCHCOD
Combined Engine Power	ENGPOW
Empty Weight	WEIGHT
Load Capacity	LODCAP
Volume Capacity	VOLCAP
Maximum Speed	MAXSPD
Calibration Date	CALDTE
Calibration Interval	CALINT
Calibration Accuracy	CALACC
Date of Next Calibration	DNXCAL

APPENDIX IV Cont'd

Maintenance

Attribute	Code
Machine Code	MCHCOD
Job Number	JOBNUM
Site Code	STCODE
Machine Hours	MACHRS
Maintenance Date	MTDATE
Last Regular Service Date	LSDATE
Service Interval	SRVINT
Maintenance Interval	MNTINT
Next Service Date	NSDATE
Equipment Fitted	EQPFIT
Fitter's Name	FITNME
Salvaged?	SLGED?
Date of Salvage	SLVDTE
Overhauled?	OVHLD?
Date Overhauled	OHLDTE
Engine Oil Check?	ENGOL?
Transmission Oil Check?	TRNOL?
Hydraulic Oil Check?	HYDOL?
Gear Oil Check?	GROIL?
Antifreeze Check?	ANTFZ?
Despatch To	DESPTO
Loading Date	LODDTE
Despatch Date	DESDTE
Authorised Release	AUTREL

Health and Safety Checks

Attribute	Code
Health and Safety Check Date	HSCDTE
Machine Code	MCHCOD
Engineer	ENGINR
Site Code	STCODE
Machine Hours	MACHRS
Controls Functioning?	CNTFN?
Brakes Functioning?	BRKFN?
Cab Windows and Doors Okay?	CABWD?
Seat Belt Okay	STBLT?
Cab Heater Okay?	CBHOK?
Windscreen Wipers Okay?	WWPOK?
Windows and Mirrors Okay?	WMROK?
Machine Structure Okay?	MSTOK?
Hoses, Pipes and Tyres Okay?	HPTOK?
Are Warning Devices Functional?	WDVOK?
Articulation Lock Okay?	ALKOK?
Steps, Handrails, etc Functional?	SHWOK?

APPENDIX IV Cont'd

Costs

Attribute	Code
Machine Code	MCHCOD
Site Code	STCODE
Maintenance Date	MTDATE
Job Number	JOBNUM
Labour Cost Quantity	LNCOST
Labour Rate	LBRATE
Labour Cost	LBCOST
Travel Miles Quantity	TMLSQT
Travel Miles Rate	TMLSRT
Travel Hours Quantity	TRVQNT
Consumables Quantity	CONQNT
Consumables Rate	CONRTE
Consumables Cost	CONCST

APPENDIX V: Evaluation Questionnaire and Correspondence with Independent Consultant

UNIVERSITY OF WOLVERHAMPTON

INTELLIPLANT
PERFORMANCE EVALUATION QUESTIONNAIRE

SECTION A: General

1. Type of Organisation:

_______________________________________(Plant Hire/Contracting/Other)

2. If 'Other' Please specify:

____

3. Number of Plant Locations (if more than one site): ____________________

4. Please list the various types of plant items you mostly utilise/hire/maintain and based on which you supplied historical data for the performance evaluation of INTELLPLANT (e.g. wheel loaders, hydraulic excavators, etc).

____

____

____

SECTION B: On-line Data Entry/Update

4. How would you rate the following data entry modes of INTELLIPLANT (1= Bad, 2= Fair, 3=Good, 4= Very Good, 5 = Excellent). Please circle as appropriate.

SPECIFICATION data entry	1 2 3 4 5
PLANT INVENTORY AND MAINTENANCE data entry	1 2 3 4 5
COSTS data entry	1 2 3 4 5
PARTS COSTS data entry	1 2 3 4 5
GENERAL UTILISATION data entry	1 2 3 4 5
WEEKLY UTILISATION data entry	1 2 3 4 5

5. How would you rate the following data updates of INTELLIPLANT (1= Bad, 2= Fair, 3=Good, 4= Very Good, 5 = Excellent). Please circle as appropriate.

SPECIFICATION data update	1 2 3 4 5
PLANT INVENTORY AND MAINTENANCE data update	1 2 3 4 5
COSTS data update	1 2 3 4 5
PARTS COSTS data update	1 2 3 4 5
GENERAL UTILISATION data update	1 2 3 4 5
WEEKLY UTILISATION data update	1 2 3 4 5

<u>SECTION C: On-line File History Reporting</u>

6. How would you rate the following on-line file history reporting by INTELLIPLANT (1= Bad, 2= Fair, 3=Good, 4= Very Good, 5 = Excellent). Please circle as appropriate.

APPROVAL FOR MACHINE RELEASES	1 2 3 4 5
DESPATCHED EQUIPMENT	1 2 3 4 5
FAULT CODES AND FREQUENCIES	1 2 3 4 5
HEALTH AND SAFETY MAINTENANCE REPORTS	1 2 3 4 5
MACHINE PRODUCTIVITY PARAMETERS AND STATUS	1 2 3 4 5
MACHINE WITH REMARKS AND PENDING JOBS	1 2 3 4 5
MACHINE HOURS TO DATE AND NEXT SERVICE DATES	1 2 3 4 5
MAINTENANCE COSTS BY JOB NUMBER	1 2 3 4 5
PLANT TRANSFER, WARRANTY AND CAL. DETAILS	1 2 3 4 5
PURCHASED, OVERHAULED AND SALVAGED EQUIPT.	1 2 3 4 5
SUMMARY OF HIRED MACHIINES	1 2 3 4 5

SECTION D: Weekly Plant Breakdown Duration Forecasting

7. How would you rate the weekly plant breakdown duration forecasting capability of INTELLIPLANT. Please rate in terms of the following criteria (1= Bad, 2= Fair, 3=Good, 4= Very Good, 5 = Excellent). Please circle as appropriate.

Interaction with the Graphical User Interface of the MBMS	1 2 3 4 5
Range of models provided within the MBMS	1 2 3 4 5
Ease of Selection of Models	1 2 3 4 5
Accuracy of Predictions by the MBMS	1 2 3 4 5
Enhancement of plant information management	1 2 3 4 5
Enhancement of plant information decision support	1 2 3 4 5

General Comments (Kindly supply any other useful information here:

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Thank you for your time. Please note that all feedback received will be treated in strict confidence.

Mr David Oloke
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20th December 2002

Dear Mr Oloke

Re: plant and equipment management software

Thank you for forwarding me a copy of your software (via Dr David Edwards, Loughborough University). IRAS Group have now reviewed the said software and can confirm that both the technical and theoretical design of your product is suitable for inclusion onto our website.

Having recently met representatives from JCB (the product owner), we confirm that they are satisfied with the product although they have recommended minor changes to the actual aesthetics of the package and have identified possible further inclusions to it. Nevertheless, we both feel that you have developed a first class software product when considering the time and resource constraints imposed upon you.

Iras, JCB, Dr Edwards and yourself need to meet urgently post your viva voce in order for us to progress this matter and finalise the contract with your sponsor. In order for me to do this, I would appreciate a latest copy of the said software on CD and a range of dates that you could attend such a meeting, at JCB Rocester, sometime during March.

I look forward to hearing from you in due course and wish you every success with your new position at Wolverhampton.

Yours sincerely

M.Showell

Mrs Maureen Showell
Director